

Progress in Ultrafast Photonics

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Recent progress in ultrafast photonics is reviewed with special emphasis on the research and development activities in Japanese research institutions in the field of optical communication and related measurement technologies. After summarizing the physical natures of ultrashort optical pulses, selected topics are reviewed on such as (1) ultrahigh-bit-rate optical communication employing the combination of optical time division multiplexing (OTDM) and wavelength division multiplexing (WDM), (2) optical components for ultrafast photonics with emphasis on all optical switches including semiconductor optical amplifiers, cascaded second order frequency converters, semiconductor saturable absorber switches, organic dye saturable absorber switches and bistable semiconductor lasers, (3) microwave photonics, emphasizing millimeter-wave/photonics communication technologies, and (4) high-speed optical measurements featuring both compact femtosecond pulse source development and rf magnetic field imaging. Some comments on the future prospect of ultrafast photonics are also given. It is concluded that in order to bring the powerful and versatile capability of ultrafast photonics into the real world, further collaboration between photonics specialists and production engineers/information specialists is strongly desired.

KEYWORDS: laser, photonics, optoelectronics, optical communication, microwave, optical measurement, nonlinear optics, optical fiber, ultrashort pulse

1. Introduction

Optical phenomena have been attracting increasing attention in view of their potential capability to handle a large volume of information, for acquisition, transmission, processing, storage and display of data. Such capability is closely connected to the fundamental physical nature of electromagnetic waves at optical frequency. The naming of “photonics” is widely employed to express the optical science and technology for information handling, analogous to the naming of “electronics”, which originally meant the science and technology of electrons for information handling.

Among the variety of optical phenomena, the generation and control of ultrashort optical pulses have made substantial progress in the last decade.¹⁾ For example, the generation of ultrashort optical pulses less than 5 fs ($\approx 10^{-15}$ s) has been realized. Prototypes of soliton transmission systems have been constructed and their performance has been evaluated. Different types of all-optical switches have been proposed and developed, with which multiplexing and demultiplexing of digital data in the time domain in the 100 Gigabit/s range and beyond have been realized optically, now known as the optical time division multiplexing (OTDM) scheme. Combined with a wavelength division multiplexing (WDM) scheme, data transmission throughput beyond 1 Tbit/s ($\approx 10^{12}$ bit/s) in a single fiber has been demonstrated. Using femtosecond optical pulse as a probe

beam, high-speed measurement techniques were developed with a temporal resolution of 1 ps or less. Through the progress of related device technology, we can now handle optically high-frequency electromagnetic waves up to the THz frequency region. We call such a topical field an ultrafast photonics field.

In this article, the authors try to review the progress in ultrafast photonics with special emphasis on the research and development activities in Japanese research institutions. After summarizing the physical natures of ultrashort optical pulses, we reviewed (a) ultrahigh-bit-rate optical communication, (b) optical components for ultrafast photonics, (c) microwave photonics, (d) high speed optical measurements. Some comments on the future prospect of ultrafast photonics are also given. The research status and the prospects of ultrafast photonics in Japan during 1990's were reviewed in [ref.2](#). In the present article, we mainly review the progress since then.

The science and technology of ultrashort laser pulses have made substantial progress also in generating terawatt class optical pulses at visible spectral region, in converting them to ultrashort X-ray pulses, and in chemically or physically processing materials using laser pulses. To concentrate on the information aspects, we have omitted these ultrafast power optics fields from the present review, although some of the physics are closely related.

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2. Fundamental Property of Optical Pulses and their Propagation Characteristics

Ultrashort optical pulses have some unique properties over conventional optical waveforms with slowly varying amplitude, such as (a) energy localization in a time domain, (b) a large instantaneous electromagnetic field suitable for inducing substantial nonlinear optical effects under a modest average power condition, and (c) broadening in spectral width inversely proportional to temporal pulse width. Therefore an ultrashort laser pulse can no longer be regarded as monochromatic light; hence the spectral dispersion of the medium should always be considered.

2.1 Fourier transform limit

Let $E(t)$ be the optical electric field amplitude and $A(\omega)$ be the spectral amplitude, where ω is the angular frequency. They are related to each other by the Fourier transform

$$E(t) = \int A(\omega) \exp[-i\omega t] d\omega. \quad (1)$$

If the temporal waveform is expressed by the Gaussian function

$$E(t) = E_0 \exp[-(t/\tau)^2], \quad (2)$$

the corresponding spectrum is

$$A(\omega) = A_0 \exp[-(\omega/\Delta\omega)^2]. \quad (3)$$

Here, τ and $\Delta\omega$ are the $1/e^2$ widths of the pulse power in time domain and angular

frequency domain, respectively. The Fourier transform of $E(t)$ gives the inverse proportionality relationship

$$\tau \cdot \Delta\omega \geq 2. \quad (4)$$

If the amplitude E_0 is constant and optical carrier $\exp[i\omega_0 t]$ is monotonic, the equality relationship holds. Such a pulse is called a "Fourier-transform-limited" pulse. On the other hand if the central frequency ω_0 drifts within the pulse duration, the pulse is called a "chirped" pulse. In this case the inequality holds. Therefore the product $(\tau \cdot \Delta\omega)$ is a measure of the spectral stationarity of the ultrashort optical pulses.

2.2 Propagation of ultrashort pulse through optical fiber: Soliton transmission

In 1973, Hasegawa found that the inclusion of the third order nonlinear response (optical Kerr effect) of an optical fiber into the electromagnetic wave equation leads to a nonlinear ordinary differential equation of the soliton type for the envelope function, known as the nonlinear Schrödinger equation (NSE)

$$i(\partial E / \partial z) - k''(\partial^2 E / \partial T^2) + g|E|^2 E = 0. \quad (5)$$

Here k'' represents the linear dispersion of the fiber, and g is a coefficient which is proportional to the optical Kerr coefficient of the fiber. Note that the time variable t is transformed to $T=(t-k_0 z)$, where k_0 is the propagation constant at the central angular frequency ω_0 .

It was predicted that under suitable conditions the pulse maintains the initial waveform after propagating through the single mode optical fiber with finite spectral dispersion characteristics.^{3,4)} Under a linear approximation the same spectral dispersion causes the broadening of pulse width after propagation, limiting the transmission bit rates. An important assumption in deriving the nonlinear Schrödinger equation is that the optical frequency of interest is in the anomalous dispersion region of the fiber, where it has the positive group velocity dispersion, or a negative value of the second-order dispersion coefficient $\beta_2=(\partial n / \partial \omega)$. In accordance with the prediction by Hasegawa, Mollenauer *et al.* of Bell Labs. and Nakazawa *et al.* of NTT Labs. successfully demonstrated soliton transmission experiments.^{5,6)} In 1999, Nakazawa also achieved 1.28 Tbit/s data transmission without employing wavelength division multiplexing (WDM) scheme.⁷⁾

2.3 Dispersion-managed soliton

The soliton transmission system consists of an array of erbium-doped optical amplifiers (EDFAs) in order to maintain the peak amplitude to induce sufficient nonlinear response of the fiber. Due to the spontaneous emission events in EDFAs, the accumulation of intensity noise is inevitable. However, the nonlinear response also causes the random fluctuation of central frequency for individual pulses. If the overall dispersion of the fiber cable is nonzero, the frequency fluctuation is converted into the fluctuation of arrival time, or timing jitter, is induced. This effect was found to be a serious

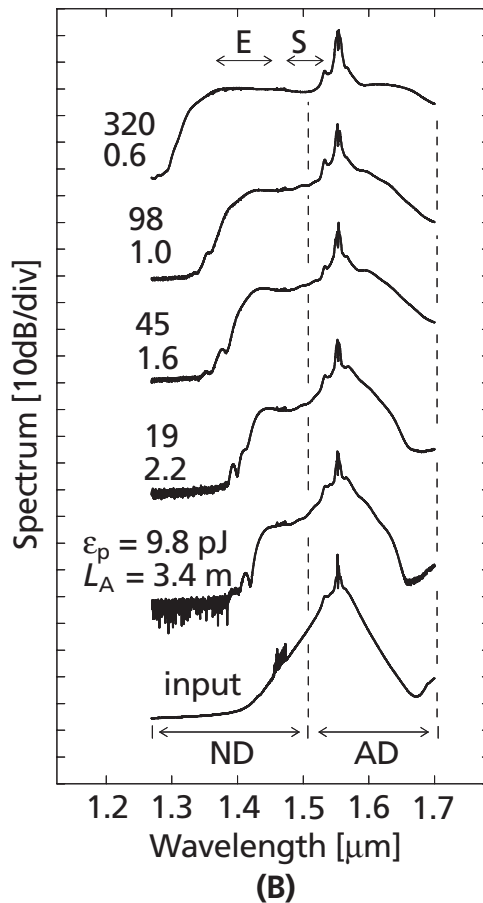
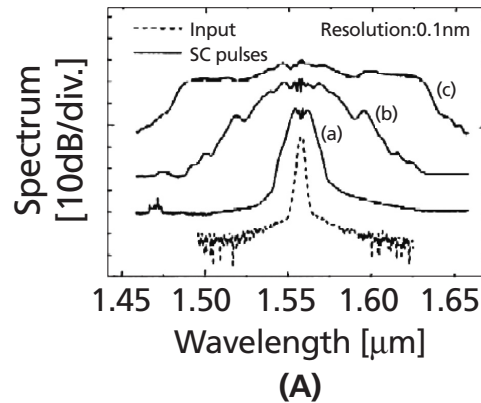


Fig.1. Super-continuum (SC) pulse generation using dispersion-flattened fiber. (A) Low-noise SC pulse generation using normal dispersion fiber (Takushima *et al.*¹¹⁾). Curve (a) 45 mW; curve (b) 140 mW; curve (c) 210 mW. The dotted curve shows the spectrum of the incident pulse. (B) Externally flat SC spectrum generation using anomalous dispersion fiber (Igarashi *et al.*¹⁹⁾). ϵ_p is the energy of incident pulse, L_A is the length of the anomalous dispersion fiber. E and S denote E and S bands, respectively. ND and AD indicate the spectral regions of normal and anomalous dispersion.

restriction in the design of the system (Gordon–Haus limit).

In 1995 Suzuki of KDD Labs. proposed a novel scheme to suppress this timing jitter. The new scheme employs the cascade connection of positive dispersion fibers and negative dispersion fibers.⁸⁾ For most of the transmission length, positive dispersion fibers are employed, so that the soliton effect transmission is ensured. Meanwhile a small proportion of the length is filled with a strongly negative dispersion fiber, so that the overall accumulated dispersion is nearly compensated. With this scheme the fluctuation of the central frequency is not converted into timing jitter. More recently the group of Suzuki at KDDI Labs. performed a field test of TDM/WDM 2.52 Terabit/s throughput system along a span of 80 km by combining TDM at 40 Gbit/s with dispersion-managed soliton transmission cables and a WDM of 63 wavelength channels.⁹⁾

2.4 Control of pulse shape and spectrum by fiber nonlinearity

With the decrease in pulse width, the spectral width becomes much broader, and more interesting phenomena appear.

Firstly we summarize the nature of the higher order soliton pulse. The solution of the nonlinear Schroedinger equation is stationary or converges to a hyper-secant (sech) waveform, if the peak power P_1 satisfies the threshold condition

$$P_1 = 0.78 \lambda^3 |D| (\pi W_0^2) / (\pi c n_2 \tau_{FWHM}^2), \quad (6)$$

where λ is the wavelength, D is the group velocity dispersion (GVD), (πW_0^2) is the effective core area of the fiber, c is the speed of light, n_2 is the nonlinear refractive index, and τ_{FWHM} is the pulse width (full width at half maximum). This pulse is called the $N=1$ soliton. For $N=1$, the pulse shape is not distorted through the equilibrium mechanism between the nonlinear phase shift caused by the optical Kerr effect and the linear phase shift caused by the anomalous dispersion. At higher peak power levels, higher order solitons are excited. Waveforms for higher order solitons change periodically. For the $N=3$ soliton, pulse width becomes narrower at $z=z_0/3$ and $z=2z_0/3$ while at $z=z_0$ it restores to the width at $z=0$. Here z_0 is the soliton period. This effect can be used as a method for pulse compression. In handling the ultrashort pulses below 1 ps, the spectral broadening is enhanced. In this situation higher order dispersion terms cannot be neglected as described below.

Secondly we discuss the progress in the generation of a very broad spectrum using a normal dispersion fiber, namely, when β_2 is positive. In this case efficient and stable spectral broadening, so-called supercontinuum (SC) generation, is possible through the optical Kerr effect under a special condition that an extremely low value of normal dispersion is provided in a wide range of wavelength as discovered by Morioka *et al.* of NTT.¹⁰⁾ This latter condition is provided by a normal-dispersion-flattened fiber. According to Takushima and Kikuchi of University of Tokyo this condition has an advantage of generating a low noise supercontinuum¹¹⁾ [Fig. 1(A)].

Thirdly, we describe the effect of higher order dispersion terms. Generally, the dispersion function of an optical fiber has a concave curvature over the near-infrared-wavelength region. When the spectral bandwidth of an optical pulse is extremely broad, the third- and fourth-order dispersion effects are not negligible indicating that the method based on the standard NSE scheme is not appropriate but the *generalized* NSE scheme should be utilized. The latter includes the higher order dispersion effects and nonlinear effects besides the optical Kerr effect. Indeed, the phenomena affected by these higher order terms have been observed experimentally. Regarding the third-order dispersion (TOD) effects, Nishizawa¹²⁾ reported the soliton self-frequency shift. The presence of the dispersion slope combined with the stimulated Raman scattering phenomenon causes it. Some trials have already been performed so as to apply this effect to fiber-optic pulse generation with wavelength tunability. In the meantime, Futami *et al.* reported the splitting of an optical pulse,¹³⁾ which is again due to the TOD effect. The spread of the spectrum over a zero dispersion wavelength leads to two different behaviors of spectral components depending on the sign of the GVD value. Regarding the fourth order dispersion (FOD), no direct evidence has been observed for standard optical fibers. The situation is different for a bunch of dispersion-flattened fibers (DFF), where the influence of TOD is minimized intentionally and the FOD nature is more emphasized consequently. Similar but more enhanced effects can be induced in photonic crystal fibers. For example, the supercontinuum (SC) generation

in a photonic crystal fiber provides a degree of spectral expansion well beyond an octave on the basis of their enhanced nonlinearity and, therefore, wide-range dispersion characteristics and higher order dispersion effects are expected to play significant roles.¹⁴⁾ In such a case, however, conventional analysis on the basis of any NSE schemes can no longer be applied since the frequency range of interest is far beyond the most fundamental assumption for the NSE schemes, namely the assumption of slowly varying amplitude.

Here, we focus on two simple cases where the generalized NSE scheme is still effective and, therefore, the effect of FOD can be clarified deductively.

The first example is the fiber-optic SC generation featured by FOD in anomalous DFF. Besides the SC generation scheme in a normal DFF, which was mentioned above, more sophisticated and interesting features are given in the anomalous DFF cases. Tsuchiya, Igarashi *et al.* of the author's group discovered the parametric gain generation at a specific frequency offset which is attributed to the FOD effect¹⁵⁾ [Fig. 1(B)]. A flat spectrum over 150 nm was recorded. For the generation of an extremely flat SC spectrum with an extremely short fiber length, the parametric gain generation in the shorter wavelength range plays an essential role through the nonlinear phase matching mechanism originating from the FOD effect. A similar observation was reported for a photonic crystal fiber.¹⁶⁾

The second example is the achievement of the ultimate limit of fiber-optic soliton compression governed by the combination of the anomalous dispersion bandwidth of the fiber and the highest available soliton order¹⁷⁾ (Fig. 2). The former factor is again determined by the FOD characteristics.

3. Ultrahigh-Bit-Rate Optical Communication

3.1 Need to increase communication capacity

There is a general trend in modern society to generate and consume as much information as possible. Having more information, one

acquires more chance to create new activity, which demands acquiring further information. This positive feedback mechanism may be an underlying motivation of information society. The high bit-rate transmission systems for the intercontinental submarine network reached nearly 1 Tbit/s throughput. Also new services for Internet end users create a strong demand for a high bit-rate metropolitan network supporting more than 100 Gbit/s throughput. In Japan broadband mobile telephone services of transmitting still- and video-pictures are rapidly in progress. Both high-capacity transmission technologies and switching node (router) technologies are urgently demanded.

3.2 WDM and TDM

To meet these demands there are two major approaches to generating multiplexed digital signals and sending them through optical fibers. One is wavelength division multiplexing (WDM) and the other is time division multiplexing (TDM). In the WDM system, the system throughput is given by the product of the wavelength channel number and bit-rate per channel. In a TDM system of single wavelength, the throughput is the bit rate itself. The technical challenges for WDM are the channel spacing and the overall bandwidth in the optical frequency domain. The technical challenges for TDM are the switching speed of the multiplexer in the sender unit and the AND logic speed of the signal/clock bits of the demultiplexer in the receiver unit. The signal distortion due to fiber dispersion and nonlinear response is the common problem.

To maximize the throughput a combination of WDM and TDM is widely employed. Note that in the ideal WDM/TDM system the overall throughput is not dependent on bit rate, but is governed by the bandwidth of the available optical spectrum. This comes from the Fourier transform relationship between pulse width and spectral width. In order to increase bit rate, we need to use shorter pulses, which occupy a wider spectral width per channel. Therefore the channel interval should be larger. The ideal setting for highest throughput is obtained when the channel interval is most efficiently occupied by a pulse spectrum. This system is called a dense WDM (DWDM) system. Considering the fact that throughput is defined as the product of bit rate and channel number, together with the fact that the bit rate is proportional to the channel interval, the product simply gives rise to the overall available bandwidth.

The guidelines of bit rate selection come from the choice of the granularity of the information. In multi-gigabit systems, smaller numbers of packets containing larger numbers of bits are easier to handle than larger numbers of finer packets. Therefore, increasing bit rate is an attractive challenge for both electronic multiplexer and for optical multiplexer. Presently the highest bit-rate available with the electronic multiplexer/demultiplexer module is

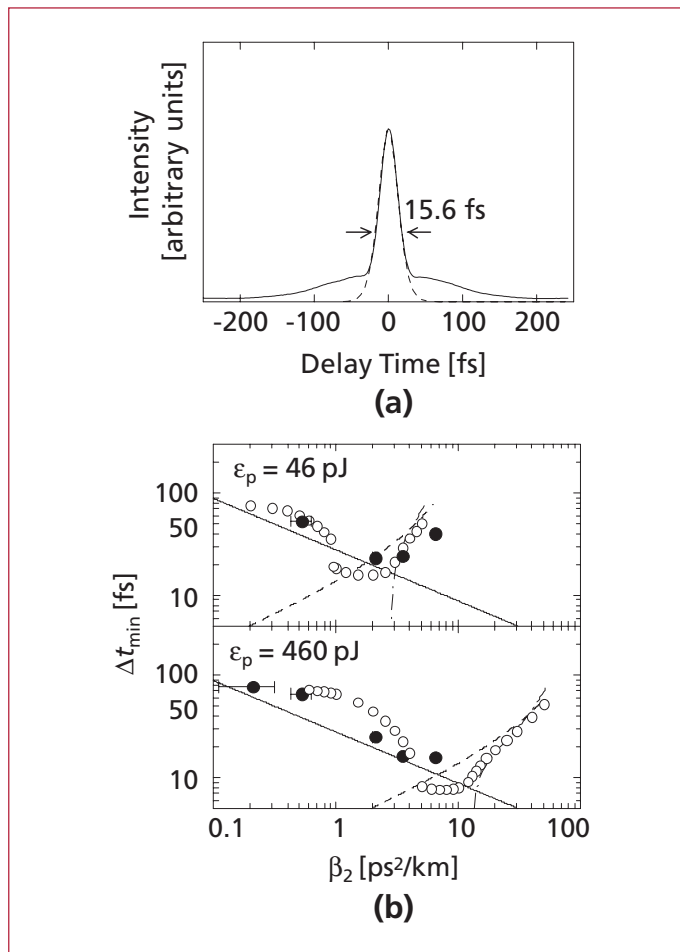


Fig. 2. Soliton effect pulse compression below 20 fs controlling fourth order dispersion (Igarashi et al.¹⁷⁾). (a) Second harmonic autocorrelation trace. FWHM is 16 fs. (b) Dependence of minimum pulse width ($\Delta t_{\min}$) on second order dispersion β_2 . $\circ$ is for the calculated pulse width employing the generalized NSE scheme, whereas $\bullet$ is for the measured data. Dotted curve: minimum pulse width simulated for the soliton compression without considering the higher order dispersion terms. Real curve: minimum pulse width given by the inverse of the anomalous dispersion bandwidth of the fiber, which originates from the fourth-order dispersion. Dotted-dashed curves: ϵ_p -limits with varying second-order dispersion.

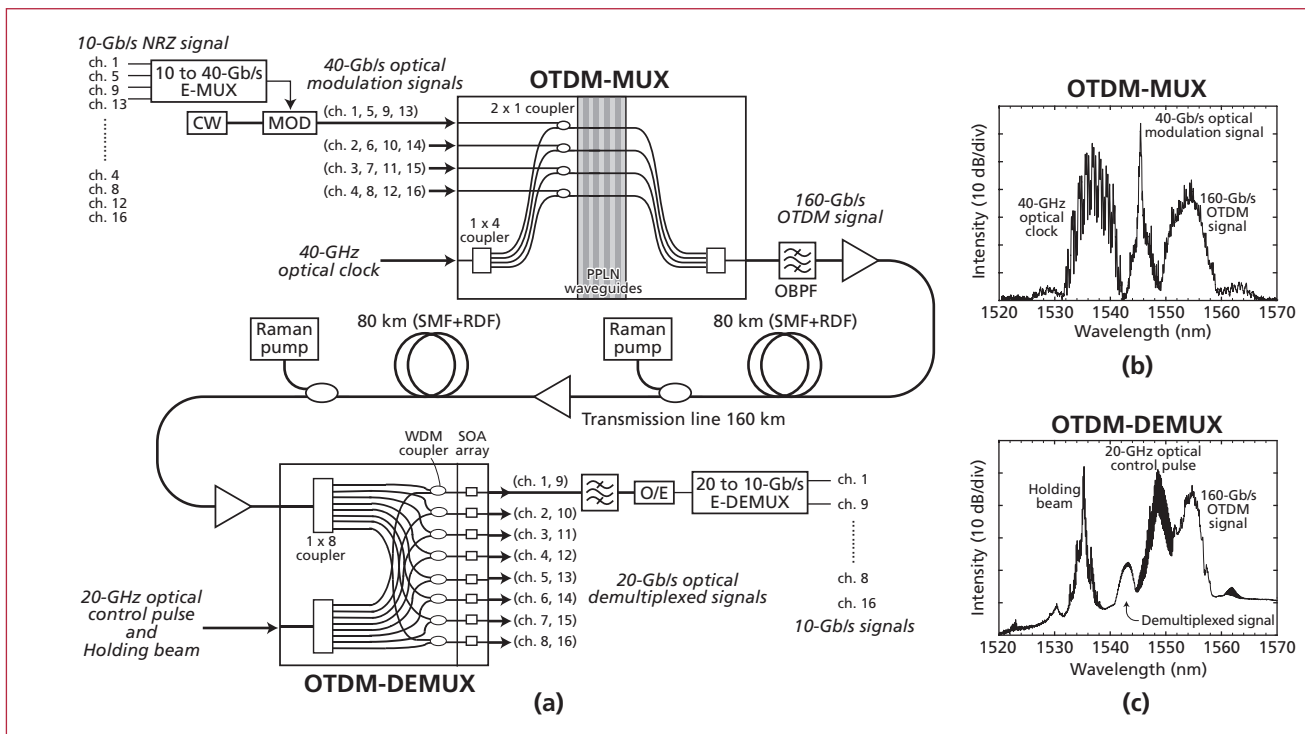


Fig. 3. (a) Experimental setup of 160 Gbit/s transmission with all-channel independent modulation multiplexer (MUX) and all-channel simultaneous demultiplexer (DEMUX). E-MUX: electrical MUX; MOD: LiNbO₃ intensity modulator; OBPB: optical bandpass filter; SMF: single mode fiber; RDF: reverse dispersion fiber; O/E: optoelectronic converter; E-DEMUX: electrical DEMUX. (b) Measured optical spectra at the exit of OTDM-MUX. (c) Measured optical spectra at the exit of OTDM-DEMUX (Ohara *et al.*¹⁹).

40 Gbit/s. Beyond that we need to use optical multiplexing/demultiplexing technology. This latter technology is called optical time division multiplexing (OTDM) technology.

One of the most realistic implementations of the DWDM transmission system was demonstrated by Miyamoto *et al.* of NTT.¹⁸ In order to suppress the data quality degradation due to fiber nonlinearity, the return-to-zero (RZ) modulation format is superior to non-return-to-zero (NRZ) format. However, the RZ format has the drawback of consuming a bandwidth two times broader than NRZ. To achieve dense WDM transmission, a novel scheme called a carrier-suppressed RZ (CS-RZ) format was proposed, where the neighboring bit has a π phase shift using cascaded electrooptic modulators. With this scheme the required bandwidth is narrowed to be 1.5 times broader than that for the NRZ format. Using this scheme a prototype 1 Tbit/s throughput system was constructed with 25 wavelength channels (1570–1590 nm) and 43 Gbit/s for each channel. A bit-error-rate (BER) less than 10^{-9} was confirmed after transmission of 90 km.

3.3 Optical time division multiplexing by all optical switches

Most digital electronic circuits are composed of transistor switches. In each of these transistor switches electrical gate voltage controls channel current flow. The bandwidth corresponding to response speed of the switch is limited by the time constant determined by gate capacitance and load resistance, usually not exceeding 100 GHz. At a signal flow of more than 40 Gbit/s, all optical switches have better potentials. All optical switches utilize various types of photon-photon interaction, so that the optical gate pulse can control the transmittance of the signal pulse. A variety of all-optical switch principles have been proposed and investigated. These will be discussed in §4. Here, we introduce two realistic transmission system trials using an ultra-short pulse and all-optical switches. One has been reported by Ohara (NTT), Fejer (Stanford University) *et al.*,¹⁹ who demonstrated a 160 Gbit/s OTDM system transmitting data over a distance of 160 km as shown in Fig. 3. They used an integrated periodically poled lithium niobate (PPLN) plate, which ensures efficient second order nonlinear wavelength conversion because of the quasi-phase matching

effect.²⁰ The cascaded second-order nonlinearity (cascaded $\chi^{(2)}$ process) acts as the AND gate for two input optical pulses (one is a periodical pulse train with a 40 GHz repetition rate and the other is a data pulse with a NRZ format). Pulses from four gates are combined with a relative delay of 6.25 ps to form 160 Gbit/s data stream. After 160 km transmission, minimum received power ensuring BER of 10^{-9} was at worst -20 dB m. Another example of OTDM system was demonstrated by Suzuki *et al.* of Femtosecond Technology Research Association (FESTA),²¹ who showed 8×160 Gbit/s (total of 1.28 Tbit/s) DWDM/OTDM unrepeated transmission over a 140 km long standard fiber using semiconductor-based devices. The featured technologies for this success include mode-locked laser diodes (ML-LD), a supercontinuum generator, symmetric Mach–Zehnder (MZ) semiconductor switches, and pre-and post-dispersion compensators. Using a 25 nm optical bandwidth, the bit rate density is approximately $0.3 \text{ bit s}^{-1} \text{ Hz}^{-1}$.

3.4 Photonic network systems

In modern network systems, not only the signal transmission but also the signal routing is very important. The routers are composed

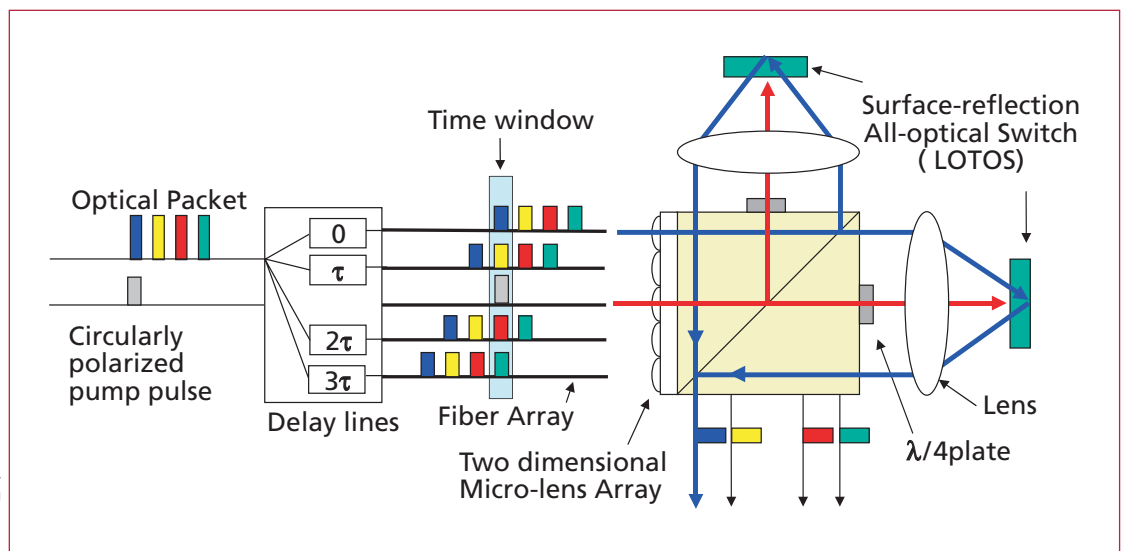


Fig.4. All-optical serial-to-parallel conversion scheme using surface-reflection switches. LOTOS: low-temperature-grown optical switch (Takahashi *et al.*²²⁾).

of digital electronics, where incoming optical data are converted into electrical signals (O–E conversion), processed electronically and then converted into optical data for output (E–O conversion). The fundamental functions of the routers are packet label recognition and redirection, tentative storage (buffering), and waveform reshaping. With the increased bit rate, O–E and E–O conversion become more difficult. The fluctuating time delay (latency) causes additional burden to the system. To overcome these difficulties, the idea of processing the data stream optoelectronically or all-optically in the routers and minimizing the burden of O/E conversion is widely accepted among communication engineers as one of the next generation network technologies. It is called photonic routing and the system composed of photonic routers is called a photonic network. First generation trials have been reported actively in recent years.

Digital data packets are composed of contents (payloads) and labels (headers), the latter of which contain the information of the destination of the data stream to be directed. The principal issue is the way how to separate and read the header portion, and to redirect the whole packet without O/E conversion of the payload portion.

One of the promising methods for such

optical signal processing is all-optical serial-to-parallel signal conversion. Takahashi *et al.* of NTT^{22–24)} developed a processing unit which can recognize the 16-bit header portion of a 1 Tbit/s data stream by converting it into a 16 channel $\times$ 82 Mbit/s parallel data flow for O–E conversion and electronic processing as shown in Fig. 4. They developed semiconductor surface reflection optical switches based on low-temperature-grown Be-doped InGaAs–InAlAs multiple-quantum-well (MQW) technology. In the recognition unit the incoming data stream is branched into 16 beams, and individual beams are given time delays of integral multiples of bit interval and illuminate the array of all optical switches together with the intense clock pulse with an 82 MHz repetition rate. Since the all-optical switch acts as the AND gate for the signal and the clock, the outgoing pulses contains the 16-bit slice from the incident data stream. This converter has an on/off ratio of more than 30 dB.

Wada *et al.* of National Institute of Information and Communications (NICT, former name: CRL) demonstrated a prototype of an optical packet switching system (OPS system) based on all-optical header recognition technology.²⁵⁾ They assume the label format of code-based labeling and bit-by-bit multiple wavelength assignment that was proposed by Kitayama and Wada of CRL.²⁶⁾ The recog-

nition of the header information is made by correlating it with those from the label bank. Individual bits of different wavelength are separated by the dispersive components such as the arrayed waveguide grating (AWG), the fiber Bragg grating (FBG), or ordinary diffraction grating. This wavelength separation functions as serial-to-parallel conversion. A prototype of 40 Gbit/s OPS system was constructed and tested. The overall BER penalty of the optical processing was found to be less than 5 dB. In correlating the header signal and signals from the label bank, they also proposed a novel holographic technique, where an angular multiplexed spectral hologram (AMSH) and an optical Fourier transform correlator play key roles.²⁷⁾ The usage of the optical Fourier transform correlator for header recognition was originally proposed by Konishi *et al.* of Osaka University.²⁸⁾ The operation is based on the frequency-to-space conversion principle. The design theory was recently developed by Furukawa *et al.* of Osaka University.²⁹⁾ Another novel wavelength routing technology is studied by Uenohara *et al.* of Tokyo Institute of Technology using high-speed wavelength-tunable semiconductor lasers with super-structure-grating distributed-Bragg-reflector (SSG-DBR) structures.³⁰⁾

Another important function of the router is the data buffering, or tentative storage

of received data. Without O–E conversion followed by storage in semiconductor memory device, Wang *et al.* of Northwestern University proposed to use a combination of a nonlinear-optical-loop-mirror (NOLM) device and a nonlinear-amplifying-loop-mirror (NALM) device.³¹⁾ The operating principle relies on four-wave-mixing loading and intracavity soliton control. The signal flow of the 20 Gbit/s packet pattern was stored for more than 6 s. Takahashi *et al.* have proposed the scheme of optical RAM, which is again based on serial-to-parallel signal conversion. This scheme is interesting for its hybrid nature of ultrafast photonics and electronics.³²⁾

4. Component Technology for Ultrafast Photonic Systems

4.1 Light source

Representative ultrashort pulse sources at communication wavelength (between 1300 and 1600 nm) are semiconductor lasers and fiber ring lasers employing erbium-doped fiber amplifiers (EDFAs). A high-performance colliding pulse mode-locked (CPM) semiconductor laser at communication wavelength was first implemented by Arahira *et al.* of Oki Electric.³³⁾ Hoshida *et al.* of University of Tokyo investigated jitter noise suppression by the injection of an electrical signal to the saturable absorber section.³⁴⁾ Wang *et al.* of NEC and Arahira *et al.* studied the stabilization by optical injection.^{35,36)} More recently Arahira *et al.* achieved 480 GHz repetition subharmonic synchronization of a CPM laser diode of short cavity length (174 μm) using a 10 GHz repetition hybrid mode-locked master laser.³⁷⁾ Because of the strong nonlinearity of the laser medium, good stabilization was confirmed. Pulse width of 0.58 ps with a timing jitter as low as 0.14 ps was obtained. Extending this technique Arahira *et al.* also demonstrated the stabilization of a 160 GHz mode-locked laser was possible by injecting a coded 160 Gbit/s optical pulse stream.³⁸⁾ Applied to optical clock extraction, excess timing jitter less than 0.1 ps was achieved at the injection power level in terms of a data signal of -3 dB m. A key feature of the semiconductor-based ultrashort pulse sources is their nonlinear section, which is the saturable absorber. The carrier dynamics of the saturable absorption

section of a monolithic mode-locked diode laser was precisely investigated by the authors' group using a pump probe technique.³⁹⁾ It was found that hole dynamics is affected by the presence of abrupt heterointerface and its improvement is necessary.

As a light source for the OTDM/DWDM system, both shortening pulse width and widening spectral width are required. The supercontinuum (SC) generation as discussed in §2.4 is suitable for this application. The system reported in ref. 21 used the SC source for generating 8 wavelength channels by slicing the spectrum with an AWG filter.

A novel SC generation with extremely flat spectral characteristics was discovered by our group at University of Tokyo as described above.¹⁵⁾ In contrast to the conventional SC configuration an anomalous-dispersion-flattened-fiber (ADFF) with the length ranging between 0.6 and 3.6 m is placed after EDFA and fiber-optic soliton compressor.⁴⁰⁾ The optimum length of ADFF is shorter for a higher pulse energy. At 320 pJ, the optimum length was 0.6 m and the spectral flatness of ± 1 dB over a 150 nm wavelength interval was observed. This behavior was interpreted as broadband optical parametric gain generation whose spectrum is extended by fourth-order dispersion (FOD) characteristics.

The stability improvement of the SC system became the next issue. Besides the dispersion profile management, one of the key factors for stability is the maintenance of polarization in the dispersion-flattened fiber. Kawanishi *et al.* of NTT proposed to employ the photonic crystal fiber (PCF).⁴¹⁾ With the proper geometrical configuration of holes at the core portion of the fiber, a strong birefringence is generated. Symmetric SC generation over 40 nm wavelength interval at 25 dB m was realized.

4.2 Pulse compression and shaping

As discussed in §2.2, the excitation of higher soliton in anomalous dispersion fiber is an efficient method of pulse compression. Miyamoto *et al.* with the members of the authors' group at University of Tokyo extended

this to the cascaded soliton compression scheme of LD-generated pulses.⁴²⁾ Using 3 stage fiber combination they obtained a compression factor of over 400 with minimum width at autocorrelation trace of 65 fs. Recently, more systematically designed cascaded fiber has yielded a 20 fs pulse [Fig. 2(a)]. Theoretical analysis has shown that the fourth-order dispersion term is non-negligible.^{43,44)} For the application of ultrashort optical pulses to real systems, the quality of optical pulses is an important issue. As pointed out by Nakazawa and his colleagues, the propagation of the fundamental soliton generates the least parametric noise.⁴⁵⁾ Therefore the adiabatic compression scheme is attractive for this purpose, where the nature of the fundamental soliton is maintained by the dispersion tailoring along the direction of propagation.⁴⁶⁾ However, optical fibers with ideal dispersion profiles are rather hard to fabricate. Igarashi *et al.* of Furukawa Electric have demonstrated a comblike profiled fiber scheme to overcome the obstacle, in which the alternate combinations of (1) nonlinear fiber parts with scarce dispersion and (2) dispersed fiber part with little nonlinearity are utilized.⁴⁷⁾ Here the compression nature can be controlled by trimming the lengths of fibers. Indeed, high-quality 160 GHz pulse trains have been reported by the same group.⁴⁸⁾

Another important technique of pulse shaping was proposed by Weiner of Purdue University based on the space-to-time conversion principle.⁴⁹⁾ More recently McKinney *et al.* of Purdue University extended the idea to direct pulse shaping for communication purposes.⁵⁰⁾

Besides the above mentioned methods, the scheme of optical reshaping, retiming and regenerating (optical 3R) has been intensively studied, which is attractive for the all-optically regenerative transmission of ultrashort optical pulses. Watanabe *et al.* of Fujitsu demonstrated a 160 Gbit/s optical 3R system based on a highly nonlinear optical fiber combined with a Mamyshev filter.⁵¹⁾ The clock recovery of the scheme is still under development. Boomholdt of HHI has demonstrated 40 Gbit/s optical 3R experiments on the basis of nonlinear semiconductor devices: injec-

tion locking into 2 mode DFB-LD and cross-phase modulation in SOA.⁵²⁾ The upper limits of the device operation speeds are key issues. For the simplification of the 3R scheme,⁵³⁾ single device operation has been investigated by Takita *et al.* of University of Tokyo and by Onishi *et al.* of Tokyo Institute of Technology, although the results of their investigation are still preliminary.^{54,55)}

4.3 All-optical switches

All-optical switches are described conceptually as four photon devices. Namely, an incident photon interacts with the switching medium, the optical properties of which are controlled by strong gate photons and determine the transmittance, or probability of generating outgoing photons. The third-order nonlinear optical effect is a typical example of such a process. Now, let E_1 , E_2 and E_3 denote the optical field amplitudes of incident photon, gate photon, and outgoing photon, respectively. They are related to each other through the third-order nonlinear optical susceptibility $\chi^{(3)}$ with

$$E_3 \propto \chi^{(3)} E_2^2 E_1 \quad (7)$$

The outgoing photon appears only when both the incident photon and gate photon are present, so that the device functions as an AND gate. According to the quantum mechanical theory, the nonlinear optical susceptibility function is related to the energy levels of the interacting material via the relationship

$$\chi^{(3)}(\omega) \propto \sum_{i,j} |M_{0i}|^2 |M_{ij}|^2 |M_{j0}|^2 / [(\hbar\omega - \varepsilon_i + \varepsilon_0)(\hbar\omega - \varepsilon_j + \varepsilon_i)(\hbar\omega - \varepsilon_j + \varepsilon_0)], \quad (8)$$

where M_{0i} , M_{ij} and M_{j0} are the matrix elements of the electric dipole moment, and ε_0 , ε_i and ε_j are the energy eigenvalues of the ground state, first excited state and second excited state, respectively. Here, $\hbar\omega$ is the incident photon energy. When one of the denominator factors is close to zero, resonance enhancement is expected. On the other hand, this resonance condition induces strong linear absorption. Hence, a trade-off problem exists.

To achieve an ultrafast switching performance, a variety of materials have been tested. We can categorize them by their trans-

parency to incident photons. When incident photon energy is far from the resonance, the material is transparent so that interaction length can be long although the nonlinear susceptibility remains modest (A). Meanwhile when the resonance condition is satisfied, the material absorbs the incident photons quickly, so that interaction length cannot be long (B). When the material is a laser gain medium under a pumped condition, it is possible that resonance coexists with no attenuation (C).

A typical example of (A) is the fiber-optic nonlinear loop mirror switch (NOLM). Although the nonlinear susceptibility of silica glass is quite small, the interaction length over 1 m ensures reasonable nonlinear interaction at modest power levels. The earlier works of the Tbit/s OTDM experiment⁵⁶⁾ utilized a NOLM switch because of its relative maturity. Another approach is the use of a high $\chi^{(2)}$ material for cascaded second-order nonlinear signal conversion. Using a periodically poled lithium niobate (PPLN) waveguide structure, efficient optical frequency conversion into $(2\omega_2 - \omega_1)$ is realized, where ω_1 is the angular frequency of incident light and ω_2 is the angular frequency of control light.

Suhara *et al.* of Osaka University extensively studied the use of lithium niobate waveguide devices for optical signal processing.⁵⁷⁾ His group improved the polarization insensitivity by precisely controlling the phase velocities of the TE and TM modes.⁵⁸⁾ Kunimatsu *et al.* of FESTA demonstrated the application of this device for 100 Gbit/s demultiplexing of 250 fs pulses.⁵⁹⁾

Semiconductor optical amplifier (SOA) acting as an all optical switch belongs to category (C). It has the advantages of a high sensitivity and a low insertion loss. Although it had been suspected that the carrier lifetime limits the switching speed, Tajima of NEC demonstrated a faster response by employing the symmetric Mach Zehnder interferometer configuration.^{60,61)} Actually the switching speed is limited by the intraband relaxation time. For the InGaAs active region, the switching speed is approximately 2 ps. The operation principle is the carrier density dependent phase shift in SOA. More recently they showed the demul-

tiplexing of 336 Gbit/s signal pulse into 10.5 Gbit/s channels using the module of a hybrid integrated symmetric Mach Zehnder semiconductor switch (HI-SMZ).⁶²⁾ Schrieck *et al.* of Swiss Federal Institute, Zurich, fabricated a monolithically integrated symmetric Mach Zehnder interferometer all-optical switch and they demonstrated a switching window of 1.5 ps, corresponding to a 600 Gbit/s data rate capability.⁶³⁾ They also analyzed the effects of carrier heating, spectral hole burning, and two-photon absorption.

Another type of all optical switch based on SOA has been studied by Sugawara's group of Fujitsu. They developed efficient quantum dot semiconductor optical amplifiers (QD-SOAs) based on InGaAs self-organized quantum dot formation technology. The QD-SOA acts as an all-optical switch by the four-wave mixing (FWM) effect. The third-order nonlinear susceptibility $\chi^{(3)}$ is caused by the sum of the carrier density pulsation effect, the spectral hole burning effect, and the carrier heating effect. In the bulk and quantum well SOAs these effects interfere differently as a function of carrier density because gain peak frequency depends on carrier density. On the other hand, in the quantum dot SOA the gain spectrum is very stable due to the spike-formed density of states. Actually Akiyama *et al.* of Sugawara's group demonstrated the improved performance of four-wave mixing in QD-SOA in terms of virtually symmetric wavelength conversion with positive and negative detuning.⁶⁴⁾ This is in contrast to the conventional quantum well SOAs where FWM conversion efficiency is much larger for positive detuning than for negative detuning, which poses a problem in achieving broadband FWM operation in WDM systems.

Recently Sugawara *et al.* demonstrated ultrawide band (120 nm) operation using QD-SOA with a peak output power level of 23 dB m by improved material technology and showed high-quality waveform regeneration and reshaping at 10 Gbit/s.⁶⁵⁾

The saturable absorber action of the semiconductor offers category-B-type all-optical switching. Since the linear absorption coefficients of excitonic transition are approxi-

mately 10^5 cm^{-1} , an interaction length of less than $1 \mu\text{m}$ is sufficient. For application to high-speed switching, material processing to shorten the carrier lifetime while maintaining excitonic response is required. The scheme of low-temperature-grown GaAs is one representative for this purpose and, indeed, is well utilized for THz wave generation sources. However, the operation wavelength range of GaAs is around 800 nm and materials for 1500 nm operation were highly demanded. Takahashi and Kawamura of NTT found that Be-doped low-temperature-MBE grown InGaAs/InAlAs multi-quantum-well (MQW) structures satisfy these requirements.⁶⁶⁾ Confining the MQW layer in the Fabry-Perot cavity, they demonstrated the device acts as a sensitive, high-speed all-optical switch, and named it LOTOS (low-temperature-grown surface-reflection all-optical switch).⁶⁷⁾ For practical applications in ultrafast serial-parallel converters, developing packaging technology is also important. Takahashi *et al.* assembled a module, which consists of a LOTOS plate, a polarization beam splitter, a planar light-wave circuit (PLC) for optical delay lines, and a micro-lens array. With this module they realized 40 Gbit/s 16 bit label recognition.²²⁾ Hainberger and members of the authors' group at University of Tokyo tried an alternative approach to assemble the saturable absorber

switches in collaboration with Kodate *et al.* of Japan Womens University. Namely, a microoptical platform for all-optical demultiplexing was designed, fabricated and evaluated using diffractive optics technology (Fig. 5).^{68–70)} Elliptical zone plate arrays formed on both sides of silica plate enabled the focusing of the pump and signal beams in the same position of the saturable absorber plate. The spatial walk-off effect on multiwavelength operation was studied in detail.

The high speed recovery of saturable absorption was also realized by employing the inter-subband transition in quantum well structures according to Akiyama *et al.* of FESTA.^{71,72)} To tune the band structure to 1500 nm transition, a coupled quantum well structure of AlAsSb/InGaAs/AlAs/InGaAs/AlAsSb was designed. The use of wide-gap cladding and barrier materials (AlAsSb and AlAs) ensured the reduction in resonance wavelength. As expected the response time was as short as 690 fs. The pulse train of 1 ps interval (pulse width of 300 fs) was successfully switched. Recently Mozume, Simoyama *et al.* of the same group improved the device performance by the introduction of an AlAs intermediate layer at the interface of the InGaAs/AlAsSb barrier.^{73,74)} The realization of an abrupt interface enabled to reduce

the saturation energy density as low as $34 \text{ fJ}/\mu\text{m}^2$ and the switching of 150 fs pulses with control pulse energy of 10 pJ was confirmed.

Another group of materials which exhibit sensitive absorption saturation and high speed recovery is the organic dye of J-aggregate structures.⁷⁵⁾ Furuki *et al.* of FESTA demonstrated a sub-100 fs response of spin-coated squarylium dye J aggregates in the 800 nm wavelength region.⁷⁶⁾ The group also proposed a novel scheme of ultrafast serial-to-parallel optical signal conversion and named it the femtosecond large area parallel processor (FESLAP).⁷⁷⁾ The key technique of FESLAP is the simultaneous illumination of the signal beam and the control fs pulse beam over a large area of saturable absorber film, with the signal beam incident normal to the film, while the control beam incident obliquely to the film, so that the bleached stripe zone is scanned along the film with the speed depending on tilt angle. The pattern of the transmitted signal beam is spatially modulated with the temporal waveform. The collaboration group of FESTA, Fuji-Xerox and CRL (presently NICT) succeeded in demonstrating a pulse train with an 1 ps interval (pulse width of 100 fs) converted into a stripe pattern. They also developed a new material called BM: di(benzofranonyl) methanolate, whose absorption peak lies at 1100

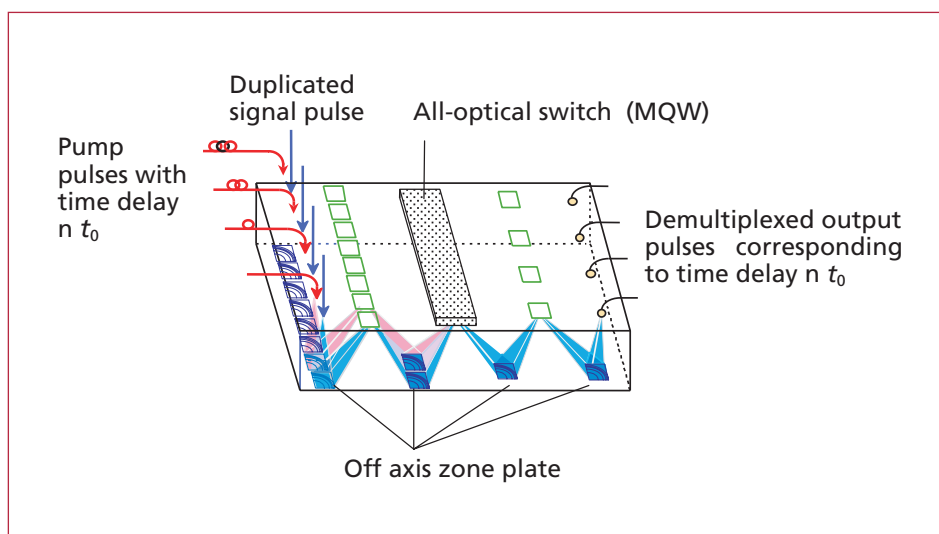


Fig.5. Concept of all-optical demultiplexing module using surface reflection switch array and free-space optics employing off-axis binary zone plate array (Hainberger *et al.*⁶⁹⁾).

nm. They managed to demonstrate the ultrafast nonlinear response of BM film at wavelengths longer than 1300 nm.

4.4 High-speed optical memory

As mentioned in §3.4 the photonic network requires a tentative storage (buffering) function for the routers. If we do not want to convert the incident packet into an electrical signal, then we need to incorporate high speed optical memories for such a buffering purpose. There are two categories for such a photonic router storage function: frame memory and bit memory. As for the former, two examples have been shown already in §3.4. The frame memory scheme is rather more practical for the buffering function although its flexibility features are not sufficient. Regarding the bit memory, there are still serious obstacles: (1) Sufficient degrees of memory integration are not available; (2) Speed of memory operation and sufficient nonlinear properties are in a trade-off relationship. Although the maturity of the technology is still not sufficient, a number of challenging trials are being pursued on a global scale. Similar to ferromagnetic memories, bistable optical devices have been a candidate for bit memory from the early stage of optoelectronics. Kawaguchi of Yamagata University, known as one of the pioneers of bistable semiconductor lasers,⁷⁸⁾ has recently proposed to use vertical cavity surface emitting laser diodes (VCSELs) as parallel addressable optical memories, because VCSELs have two metastable lasing states of orthogonal polarization.⁷⁹⁾ By injecting a linearly polarized control light pulse, the VCSEL is switched to the polarization state of the control pulse, and the state is sustained until the next pulse is incident. Takenaka and Nakano of University of Tokyo proposed and realized a bistable integrated photonic circuit including SOA. It is a directionally coupled bistable laser diode (DC-BLD), which consists of a main cavity with a saturable absorber section and a directionally coupled side waveguide.⁸⁰⁾

The injection of the control pulse to the main cavity turns the lasing on because the control pulse bleaches the saturable absorber. The injection of the control pulse to the side

waveguide terminates the lasing because the nonlinear response of the directional coupler portion extracts the photons from the main cavity.

Another bistable photonic circuit employing SOA was proposed by Dorren *et al.* of Eindhoven University of Technology.⁸¹⁾ The planar SOA is excited axially both by the signal light and by control light. The output light is sent to the polarization beam splitter and detected. The polarization state of the signal light is tilted by 45° with respect to the junction plane of SOA, so that TE and TM modes are equally excited. The polarization controller is adjusted so that the maximum output is obtained. When a strong control pulse is incident to SOA, its gain is saturated, and the phase velocities of the TE and TM modes are changed. Due to the relative phase delay, destructive interference occurs and the output power becomes suppressed for increased control power. Now consider a pair of polarization switch units (PSW1 and PSW2) combined in a similar way as a flip-flop electrical circuit. Then there occur two stationary operations: one is the state where PSW1 is high and PSW2 is low, the other is the state where PSW2 is high and PSW1 is low. By the proper triggering these two stationary states can be switched between each other. Although the experimental demonstration was performed with relatively slow pulses (150 ns) the authors expect the scheme can be extended to the 10 Gbit/s regime considering the high-speed physical processes involved.

4.5 Photodetectors

As shown in previous sections, it is not possible to manipulate large-capacity information flow only with optical technology, even though the advantage of ultrafast photonics has recently been recognized. The majority of information processing including computation, storage, pre-and post-processing in communication systems, and routing relies on the VLSI technology. Therefore the development of high-speed photodetectors in the wideband photonic system is important. In the conventional pin photodiode, there is a trade-off relationship between speed and

quantum efficiency, because thinning the absorption layer is favorable for shortening transit time, while only some of the incident photons are absorbed. To overcome this difficulty, waveguide-type pin photodiodes were developed.⁸²⁾ By edge coupling the quantum efficiency increases to nearly 100% and a cutoff frequency exceeding 50 GHz were realized. Another requirement is the heavy-duty operation characteristics. When the photodetector is used together with the optical preamplifier, the input power levels may be relatively high. In conventional photodiodes the carrier accumulation at the active region substantially deteriorates the frequency characteristics. Ishibashi *et al.* of NTT invented uni-traveling carrier photodiodes (UTC-PDs), for which carrier accumulation at input power levels of 50 mW is negligible and cut-off frequency of over 100 GHz is not deteriorated.^{83,84)} This was made possible by introducing an asymmetric heterostructure, so that only electrons are mobile and holes are blocked. UTC-PDs are also very useful in microwave photonic applications for the optical generation of high power and high frequency electromagnetic wave. Indeed, it is advantageous for the generation of higher power sub-THz signals, whose frequency range is beyond the cutoff of the device.

5. Fusion of Optical and Microwave Technologies: Microwave Photonics

Although the ultrafast nature of photonics provides scientifically and technologically attractive opportunities as described above, the wavelength ranges for efficient frequency conversion are limited because ultrashort optical pulses, intense pulse source and transparent nonlinear media or frequency conversion methods are not always available. That is, ultrafast photonics are not provided to all the wavelength range of lightwave. However, there is a means of conferring the ultrafast nature of photonics to its base band, which is one of the most important frequency bands, through fast interactions between lightwaves and electromagnetic waves. Here, the frequencies of interest range from GHz to

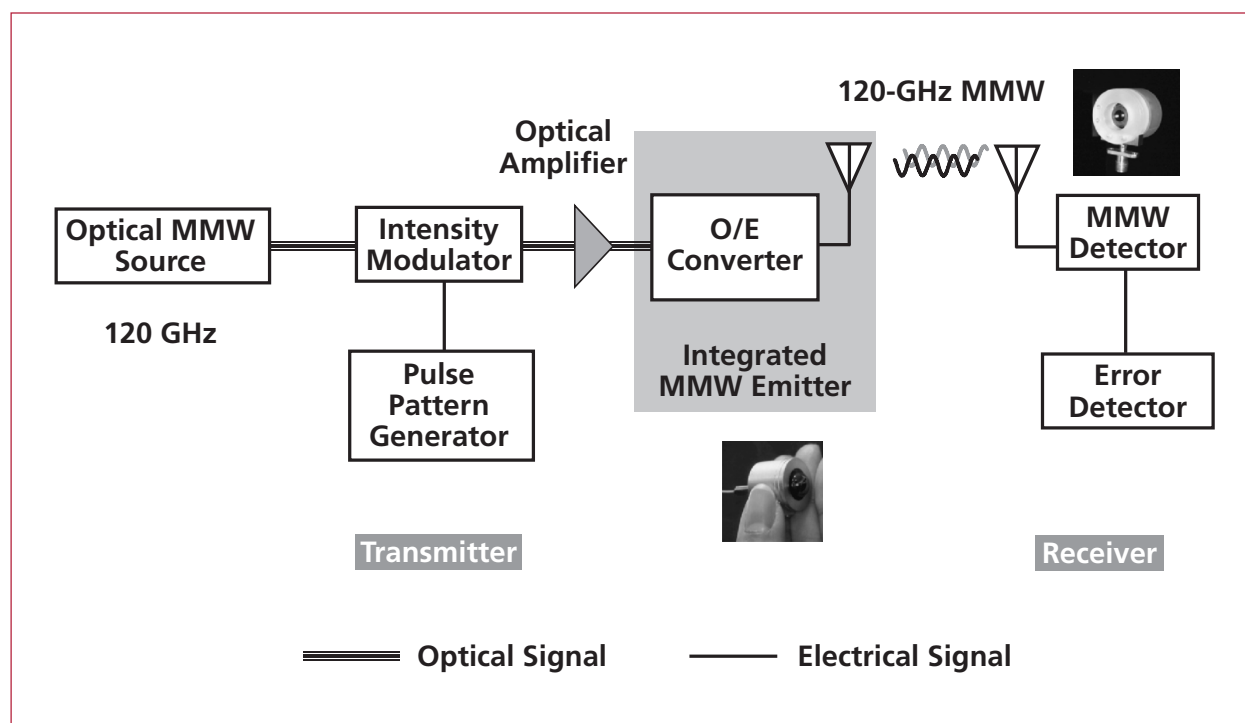


Fig.6. Wireless transmission system with 10 Gbit/s with optically generated 120 GHz carrier (Hirata and Nagatsuma⁹²⁾).

THz. Also, frequency-down-conversion techniques are effective. Together with advantages in the low-loss and high-bandwidth fiber-optic transmission, the technical field based upon the fusion of photonics and microwave technologies is growing and is called microwave photonics.⁸⁵⁾ This technological field is expected to cultivate the interdisciplinary area between two major communication technologies: fiber-optic and wireless communications. Recently, another related technical field is also growing rapidly, which is called THz photonics. This field has attracted considerable amount of interest for its application to environmental sensing,⁸⁶⁾ security,⁸⁷⁾ and important futuristic frequency resources.

Another notable aspect of microwave photonics is high-speed optical signal generation on the basis of lightwave modulation, that is, optical sideband syntheses by microwave or millimeter-wave signals. Here, the

optical modulation techniques are key issues: representative techniques include directly modulated semiconductor lasers, EO modulators, EA modulators and integrated modules of modulators and lasers. The frequency multiplication techniques are important when one wants to achieve higher frequency components beyond the device bandwidths. Yamamoto and Kawanishi of NTT have demonstrated an optical local oscillator, with which one can generate a wide range of electromagnetic waves quasi-continuously: 100 GHz–1 THz. They use the fiber-optic nonlinearity and the SC generation to multiply the available frequencies.⁸⁸⁾ Kawanishi of NICT has demonstrated another method to multiply the input frequency by electro-optical modulation. The multiple phase modulation of reciprocally traveling light waves within an integrated LN modulator gives rise to the frequency multiplication.⁸⁹⁾

What is particularly interesting here is the fact that the advanced modulation formats developed in the field of microwave technology are being applied in a practical manner to the fiber-optical transmission of digital signals currently.⁹⁰⁾ The phase shift keying techniques are good examples. This recent trend has been supported by the continuous development of integrated high speed LN modulators.⁹¹⁾

One of the high-end techniques in microwave photonics is extremely broad band wireless communication. A wireless transmission system with 10 Gbit/s has been demonstrated by Hirata and Nagatsuma *et al.* of NTT, where an optically generated 120 GHz carrier is utilized.⁹²⁾ Here, the high-bandwidth nature of photonics gives rise to the successful transmission of signals with the highest bit rate in air (Fig. 6). Sasai *et al.* of Panasonic have provided a representative microwave photo-

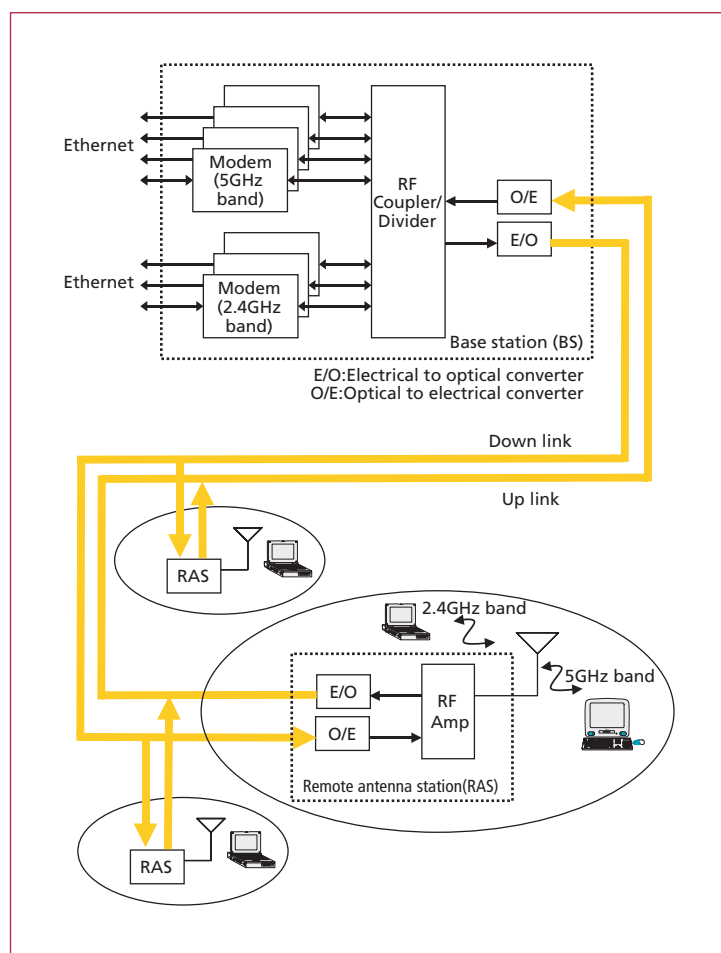


Fig.7. Configuration of photonic-link/wireless-LAN hybrid system. Thick arrows indicate photonic links for multiple services. Cost-effective use of the remote antenna stations (RAS) is the key issue (Sasai *et al.*⁹³⁾).

tics approach in a rather practical manner, where the frequency range is not necessarily high but indispensably important in the real world.⁹³⁾ The essence of the work is the flexibility provided to a wireless LAN system by the transparency of photonic links (Fig. 7). Indeed, the flexible nature and light-weight properties of fiber-optic radio wave links have attracted considerable attention from the commercial viewpoints. Through radio-on-fiber techniques, problems in radio-wave-insensitive areas such as underground shopping areas, subways, submarine tunnels and high-rise hotel buildings can be solved.

The combination of microwave photonics and nonlinear photonics has led to a considerably attractive scheme. By this technique

the locking of absolute optical phase to the highest-stable microwave signal was realized. This has already been applied to ultra-accurate clocks.⁹⁴⁾ Let us look forward to further development.

6. Optical Probing

The electrooptic (EO) effect is indispensable for optical modulation techniques. It is also very useful as the ultrafast optical measurement technique. The technique called EO sampling (EOS) was first demonstrated by Valdmanis *et al.*⁹⁵⁾ and is now a standard method for the characterization of high speed devices and circuits with 100 GHz operation frequencies or more.⁹⁶⁾ The introduction of the concept of desk-top style EO probing system

had fairly intense impact was brought on its practical usage.^{97–99)} Such a system is more convenient than the conventional EO sampling system of laboratory sizes. As its extension, a 300 GHz EO network analyzer was demonstrated by Sahri and Nagatsuma.¹⁰⁰⁾

Another trend has been brought about by optical probes based on pig-tailed LN modulators with probing metal elements attached.¹⁰¹⁾ These are attractive for far field measurement of electromagnetic wave radiation and, hence, are expected to be effective for the electromagnetic compatibility problems. However, the presence of metal parts significantly degrades the noninvasive property, which is one of the most advantageous features of optical probing techniques and is indispensable for precise analyses of very near field distribution. Almost contiguous measurement is advantageous for the diagnoses of microscopic-scale integrated circuits of high frequency and for highly dense packages. This is possible only when a metal-free nature is conferred to optical probes. In order to minimize the electromagnetic invasiveness, the use of a fiber-edge electrooptic probe is effective, where an EO crystal is glued to the edge of the optical fiber.¹⁰²⁾ The optical fiber works not only as an optical waveguide but also as a very fine metal-free EO crystal holder, providing real metal-free circumstances and accessibility to densely packaged parts on a crowded printed-circuit board.¹⁰³⁾

Magneto-optical (MO) probe is new compared with EO probes. The difference between them may originate from the fact that the magneto-optical process is generally slow, which is correct if one considers the magnetic domain inversion phenomena only. Yamazaki *et al.* of the authors' group at University of Tokyo noticed the fast nature of rotation magnetization (RM),¹⁰⁴⁾ and implemented the first RM-based optical probe with a bandwidth of more than 10 GHz.¹⁰⁵⁾ Here, the fiber-edge optical probe scheme is again utilized. Figure 8 shows the magnetic field images obtained above a GHz band-pass filter made of microstrip lines.¹⁰⁶⁾ The standing wave nature of GHz current is clearly seen, with which GHz current profiler action has been demonstrated. Note that the MO probing

scheme is complementary with the EO probing scheme and that the simultaneous combination of these could lead to clarification of local impedance in a complicated circuit. Furthermore, highly sensitive MO probes are effective to measure the variation of current distributions in low impedance patterns such as ground/power lines.¹⁰⁷⁾

7. Summary and Future Prospects

In summary, the progress in the application of ultrafast photonics to information technologies is reviewed with special emphasis of the activities in Japanese research institutions. Broadband optical communication system trials employing the combination of optical time division multiplexing (OTDM) and wavelength division multiplexing (WDM) have become realistic, with electrical-optical interface data flow of 40 Gbit/s and total throughput reaching 1 Tbit/s. To meet the demand of routing high-bit-rate data flow without O-E conversion, optical header recognition and rerouting technologies are investigated thoroughly. As pulse sources for OTDM/WDM optical communica-

tion, both optically stabilized mode-locked semiconductor lasers and supercontinuum generators using the nonlinearity of dispersion flattened fibers are promising. A variety of all-optical switches for demultiplexing and other all-optical signal processing have been developed, including semiconductor optical amplifier (SOA) switches, cascaded second-order frequency converters using periodically poled lithium niobate (PPLN), semiconductor saturable absorber switches, organic dye saturable absorber switches, and bistable semiconductor laser switches.

As a measurement probe, ultrashort pulse generation and control technology are important. By cascaded soliton compression, the authors realized a semiconductor-laser-based pulse source of 20 fs width. Employing high speed uni-traveling carrier-photodiodes (UTC-PDs), novel signal processing procedures for microwave/photonics systems are developed. Electro-optic sampling technologies were extended to high-speed electromagnetic field imaging technologies. Using a small magneto-optical probe chip on the fiber end, the author was successful in the rf magnetic

field imaging of microwave components at 10 GHz. These measurement technologies are important in precisely controlling the equipment of opto-wireless systems.

It was shown that there is steady progress in the research and development of ultrafast photonics for information systems. A number of pico- and femto-second devices are close to be realized as commercial products, and novel devices and promising ideas are continuously added. Thus, the ultrafast photonics field is providing technical seeds to many information handling areas as powerful and versatile tools. However, we are still staying at some distance from the point where the technology is widely deployed to meet real world demands. Important issues should be investigated from standpoints such as reliability physics, mass productivity, interface compatibility, and system flexibility. In order to bring ultrafast photonics to the real world, photonics specialists should work together with production engineers and information specialists more closely and patiently.

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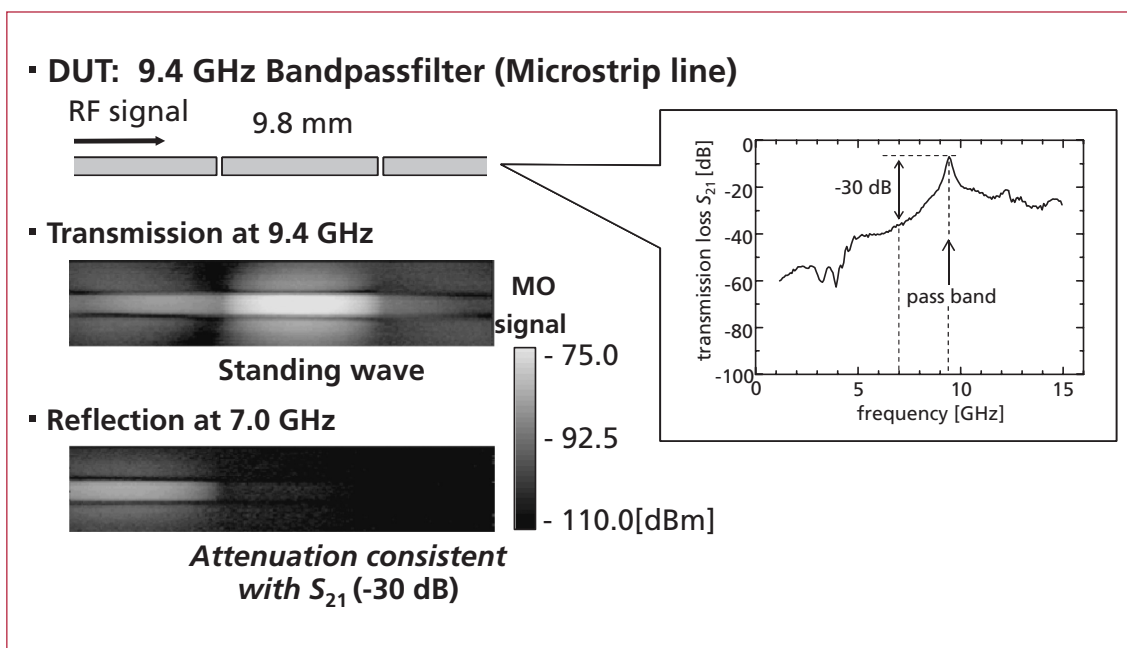


Fig.8. Magnetic field images obtained above 9 GHz band pass filter made of microstrip lines (Yamazaki et al.¹⁰⁶⁾). DUT: device under test. The inset on the right-hand side shows the electrically measured transmission loss of DUT.

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