

Wavelength Conversion Technologies for Photonic Network Systems

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This paper reviews wavelength conversion technologies for photonic network systems. A simple method of four-wave mixing (FWM) wavelength conversion using a $\lambda/4$ -shifted DFB laser and one using a polarization-maintaining highly-nonlinear dispersion-shifted fiber (PM-HNL-DSF) are presented. For both wavelength conversions, transmission experiments with dispersion compensation were performed using phase conjugation. A 10 Gb/s transmission over 100 km was done using the $\lambda/4$ shifted DFB laser wavelength converter, and a transmission over 100 km for 32 WDM (wavelength division multiplexed) signals of 10 Gb/s each was performed using the PM-HNL-DSF wavelength converter. Then, this paper discusses possible applications of these technologies to the photonic network systems.

1. Introduction

Recently much attention is being paid to wavelength conversion technology. One of the reasons for this is the strong demand for wavelength division multiplexing (WDM) communication systems. If we could convert a signal to a desired wavelength in a transmission bandwidth, it can be used to perform add drop multiplexing (ADM) and an optical cross connect using the wavelength domain in WDM systems. This enables us to realize highly flexible and reconfigurable communication systems. The application is not limited to WDM systems. If we could use a coherent nonlinear process for wavelength conversion, we can obtain a phase conjugate optical wave. This can be used for the compensation of the chromatic dispersion and nonlinearity of optical fiber to enable long-distance, high-bit rate communication.^{1),2)} The wavelength conversion technologies can also be used to perform demultiplexing of very-high-bit-rate time domain signals by converting each bit to different wavelengths.^{3),4)} There will be many more applications if we could realize higher per-

formance and compact wavelength converters.

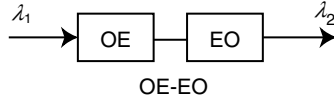
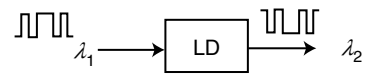
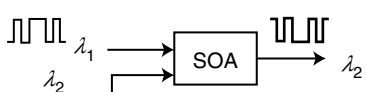
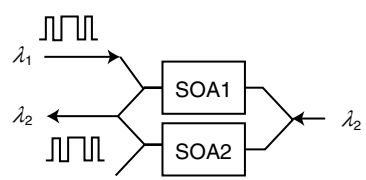
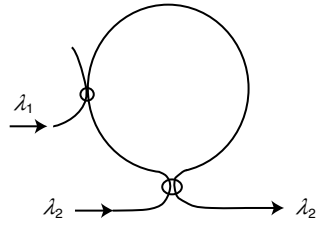
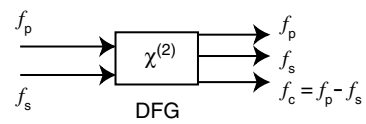
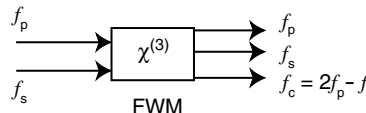
Despite such expectations and some promising experimental reports, the wavelength conversion technologies are as yet immature. The technologies that have been reported so far are the OE-EO transponder type, the gating type using semiconductor devices and optical fiber,⁵⁾⁻⁹⁾ and the coherent type, which uses nonlinear wave mixing in either a semiconductor or an optical fiber.^{1),10)-12)} In this paper we first review these three wavelength conversion schemes. Then, we describe the results of recent work we have done on wavelength conversion through four-wave mixing (FWM) using a semiconductor gain medium and an optical fiber. Lastly, we discuss the possible applications to photonic network systems.

2. Review of wavelength conversion technologies

Table 1 shows a comparison of various wavelength conversion technologies. They can be categorized into three types.

One is the OE-EO type, in which an optical

Table 1
Wavelength conversion technologies.

Type	Configuration	Features
OE-EO type	 <p style="text-align: center;">OE-EO</p>	<p>~10 Gb/s</p> <p>Speed is limited by electronic circuit.</p>
Gating type		<p>~40 Gb/s</p> <p>Waveform is inverted in XGM</p> <p>Wavelength chirp is inevitable in XGM and XPM.</p>
	 <p style="text-align: center;">XGM</p>	
	 <p style="text-align: center;">XPM</p>	
	 <p style="text-align: center;">NOLM</p>	<p>~Tb/s</p> <p>Needs synchronization of signals.</p>
Coherent type (Phase conjugate wave generation)	 <p style="text-align: center;">DFG</p>	<p>~Tb/s</p> <p>Needs phase matching</p>
	 <p style="text-align: center;">FWM</p>	<p>~Tb/s</p> <p>Phase matching is easier.</p>

signal is detected by a photodetector and then amplification, reshaping, and re-timing are performed to drive a DFB (distributed feedback) laser of a different wavelength. This is simply a conventional transponder.

The second type is the optical gating wavelength converter. This type includes the cross gain modulation (XGM) scheme, which uses gain satu-

ration of a semiconductor laser or semiconductor optical amplifier (SOA) by the input optical signal.⁵⁾⁻⁷⁾ When an optical signal of wavelength λ_1 is coupled to a laser lasing at λ_2 , the lasing is quenched by the input signal. This causes modulation at the lasing wavelength, and the information on wavelength λ_1 is then transferred to λ_2 . As shown in the table, the waveform in λ_2 is

the inversion of λ_1 . The gain saturation is also used in this manner in semiconductor optical amplifiers (SOAs). In the cross phase modulation (XPM) scheme,⁸⁾ the input signal changes the refractive index of one arm of a Mach-Zehnder interferometer to modulate the other wavelength, λ_2 . The NOLM (nonlinear optical loop mirror) scheme uses the nonlinearity of optical fiber.⁹⁾ Optical pump pulses at wavelength λ_2 are launched clockwise and counter clockwise into a loop using a coupler. These two pulses cancel each other at the output. However when a signal of wavelength λ_1 is launched into the loop in synchronization with either of the pump pulses, there is a phase shift due to the change in refractive index. This breaks the cancellation condition for wavelength λ_2 to give an output. Thus the λ_1 signal is transferred to λ_2 . In the gating type wavelength conversion, the input signal modulates the other wavelength.

The third type performs coherent mixing of waves to generate a third wavelength by directly using the second-order or third-order nonlinear susceptibility of a semiconductor or an optical fiber. The difference wavelength generation (DFG) scheme¹⁰⁾ uses the second-order nonlinear susceptibility $\chi^{(2)}$. A new optical frequency, f_c , which is the difference frequency between the pump wave, f_p , and signal wave, f_s , is generated. For the input wave and the difference wave to be in the same transmission band, the pump frequency should be about twice the signal frequency. Because of this large difference in frequency between the pump and signal, the phase matching is very important in this scheme. Four-wave mixing (FWM) wavelength conversion^{1),11),12)} generates the new optical frequency, $f_c = 2f_p - f_s$, through the third-order nonlinear susceptibility $\chi^{(3)}$. Because the pump wave, signal wave, and converted waves are in the same wavelength band, the phase matching is not as important as it is in DFG. In the coherent type wavelength conversion, the converted wave is the phase conjugate (or complex conjugate) of the input signal wave, i.e., the spectrum is inverted. We

use the notation “c” to identify the conjugate signal.

The characteristic features of these wavelength conversion schemes are summarized in Table 1. In the XGM and XPM schemes using either a semiconductor laser or an SOA, the response speed is limited by the carrier lifetime in the devices. The highest response speed reported so far is around 40 GHz. Since these schemes use the carrier density change in the active medium, there arises a wavelength chirp associated with the corresponding refractive index change. The NOLM configuration enables wide-band wavelength conversion because of the large bandwidth of the nonlinear susceptibility of optical fiber. However, this scheme requires synchronization of the input pulse and pump pulse. The third category, coherent conversion, is highly attractive because of the wide bandwidth of the nonlinear susceptibility and the coherent nature of the conversion. A very fast response speed of 100 THz is expected in the $\chi^{(3)}$ of a fiber,¹³⁾ and a response speed of 6 THz has been observed in a carrier injected multiple quantum well (MQW).¹²⁾ These high response speeds allow us to perform a wide-band, format free wavelength conversion. The chirp is almost negligible because it does not significantly change the carrier density in the nonlinear medium. When we compare DFG and FWM, FWM is much simpler because the phase matching requirement is not so stringent. The fact that the converted wave is the phase conjugate of the input wave is highly attractive because it can be used to compensate for the dispersion and nonlinearity of optical fiber.¹⁾ An important issue associated with coherent type wavelength conversion using a fiber and semiconductor gain medium is that the input signal wave and the pump wave must have the same polarization. We must therefore use some means to satisfy this condition in actual applications.

Among these wavelength conversion technologies, we have been pursuing the FWM scheme because it offers feasible transparent (bit-rate free and format free) wavelength conversion and has

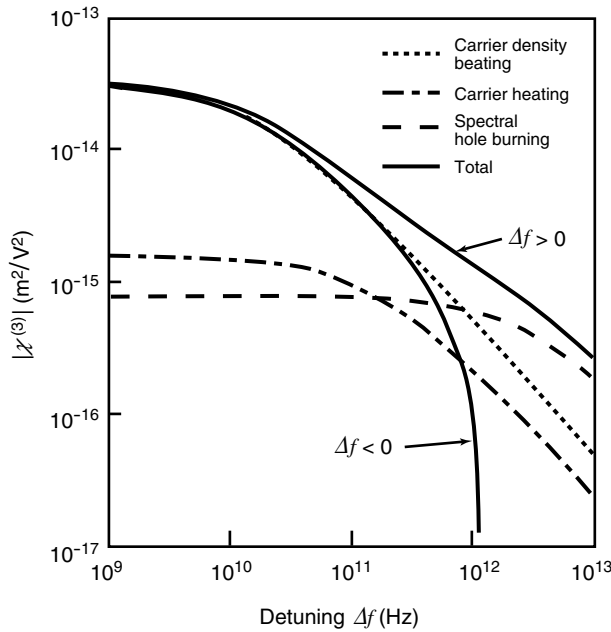


Figure 1
Calculated example of third-order nonlinear susceptibility of MQW as function of detuning.

a less stringent phase matching requirement than the DFG. In the next chapter, we describe our latest results for FWM wavelength conversions.

3. FWM wavelength conversion

3.1 FWM in semiconductor gain medium

Semiconductor gain mediums, like the active layer of an SOA or semiconductor laser, have third-order nonlinear susceptibility. **Figure 1** shows an example of the calculated third-order nonlinear susceptibility $\chi^{(3)}$ of a multiple-quantum well (MQW) structure under current injection. The nonlinear susceptibility consists of three components: the carrier density beating effect, carrier heating effect, and spectral hole burning effect. The carrier density beating effect arises from the beating of the carrier density at the beat frequency of the pump wave and signal wave and has a time constant of several ns, which is the carrier lifetime. The carrier heating effect is the beating of carrier temperature. The time constant is the LO-phonon scattering time, which is several 100 fs. The spectral hole burning component can be regarded as a gain saturation effect associated

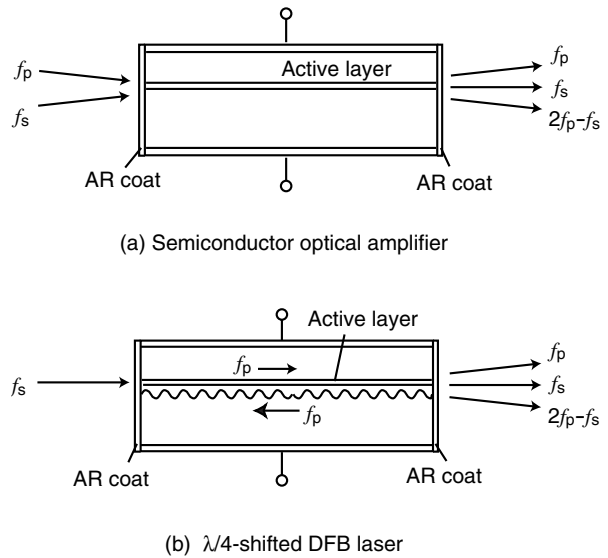
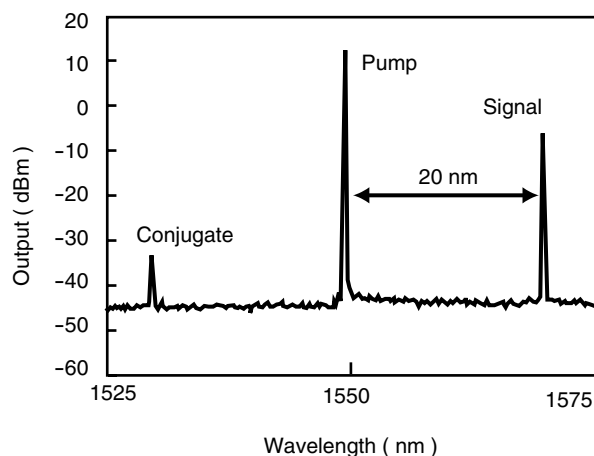


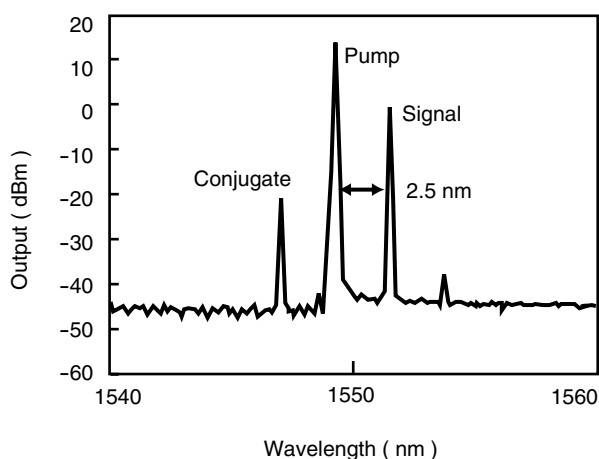
Figure 2
FWM using (a) semiconductor optical amplifier and (b) $\lambda/4$ -shifted DFB laser.

with the beating of the pump wave and signal wave. This component has a very fast time constant of several tens of fs; the time constant originates from the intra-band carrier scattering.¹²⁾ These three components are almost in phase for positive detuning ($\Delta f = f_p - f_s > 0$), i.e., when the input signal wave is on the longer wavelength side of the pump wave. However, for negative detuning ($\Delta f < 0$) the carrier density beating effect and the spectral hole burning effect are out of phase with each other and the nonlinear susceptibility $\chi^{(3)}$ becomes smaller as shown in Figure 1. This means that $\chi^{(3)}$ is asymmetric with respect to the pump wavelength. The $\chi^{(3)}$ is large for a small detuning because of the large contribution of the carrier density beating effect. What is attractive is the very large bandwidth of the hole burning component, which enables us to perform very wide bandwidth wavelength conversion.

The most popular way to perform FWM in a semiconductor gain medium has been to use an SOA as shown in **Figure 2(a)**. The pump wave and the signal wave are coupled to an SOA to generate the wavelength converted conjugate wave. We have developed a new simple method as an alternative to using an SOA. As shown in



(a) Detuning of 20 nm



(b) Detuning of 2.5 nm

Figure 3
Output spectrum of $\lambda/4$ -shifted DFB laser for detuning of (a) 20 nm and (b) 2.5 nm.

Figure 2(b), the lasing wave of a single mode laser itself is used as a pump wave and the FWM takes place within the laser cavity.¹²⁾ A $\lambda/4$ shifted DFB laser with a cavity length of 900 μm was used. This laser was designed to give stable single mode operation up to a high output power. A high lasing power is advantageous for obtaining a high conversion efficiency because the conversion efficiency is proportional to the square of the pump power. Because the internal lasing power is used as a pump, unlike in an SOA there is no coupling loss for the pump power. The long cavity also contributes to give a high conversion efficien-

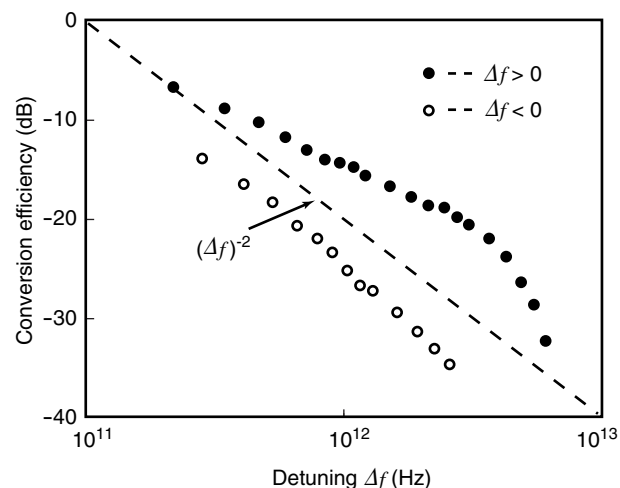


Figure 4
Measured conversion efficiency of $\lambda/4$ -shifted DFB laser as function of detuning.

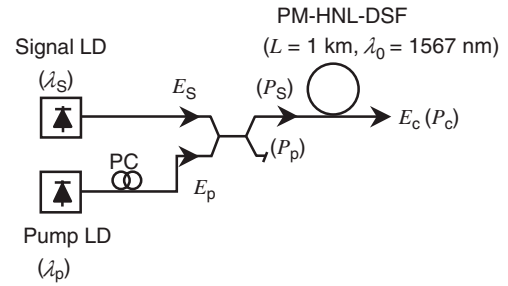
cy because of the longer interaction length of the pump and signal wave. **Figure 3** shows the output spectrum of the semiconductor laser for a large positive detuning of 20 nm (a) and for a small positive detuning of 2.5 nm (b). This figure indicates the presence of a wavelength converted conjugate wave and indicates that a higher conversion efficiency is obtained for a smaller detuning. **Figure 4** shows the conversion efficiency as a function of the detuning between the pump wave and conjugate wave. The conversion efficiency is higher for the positive detuning, i.e., when the signal is on the longer wavelength side of the pump wave. The conversion efficiency is smaller for the negative detuning. This asymmetry arises from the asymmetry in the $\chi^{(3)}$.

When we compare the FWM in a DFB laser with that in an SOA, the advantage of using a DFB laser is that it does not require an external pump source. This greatly simplifies the configuration. However, a higher conversion efficiency of 0 dB was reported for a detuning of 1 THz in an SOA,¹¹⁾ while the value was -15 dB in a $\lambda/4$ shifted DFB laser. This is because of the larger linear gain in an SOA. The linear gain in the laser is clamped at the threshold level. Recently we have developed an improved DFB laser wavelength converter in which SOAs are monolithically inte-

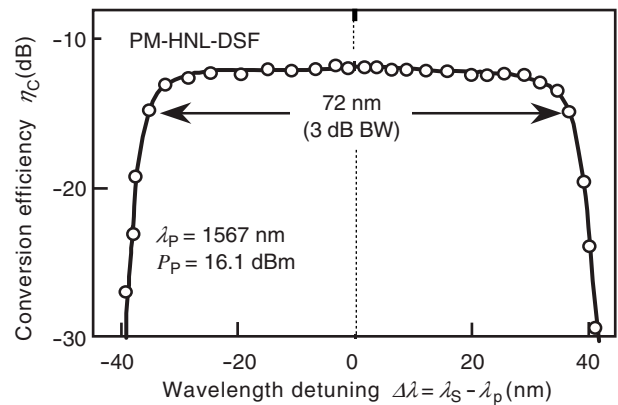
grated on both sides of the laser cavity to provide additional linear gain.¹⁴⁾ With this configuration we achieved a 0 dB wavelength conversion efficiency up to a positive detuning of 300 GHz. The efficiency was -5 dB for a 1 THz detuning. Generally the large linear gain gives a high conversion efficiency, while it gives an additional amplified spontaneous emission (ASE) noise. There will be an optimum linear gain that gives the maximum signal-to-ASE ratio. The optimum seems to lie between the SOA and the DFB laser wavelength converter. Our SOA integrated DFB laser is promising in this respect.

3.2 FWM in optical fiber

In FWM using an optical fiber, several kilometers of optical fiber are used, whereas the semiconductor device is only a few hundred microns long. Therefore the phase matching becomes an important issue. The phase matching can be done by adjusting the pump wavelength to be the zero dispersion wavelength λ_0 and by controlling λ_0 precisely along the fiber. However, there remains some fluctuation. Therefore, a highly nonlinear dispersion shifted optical fiber (HNL-DSF) has been developed to enable FWM with a short fiber length.^{15),16)} A high nonlinearity has been achieved by making the mode diameter smaller to increase the optical power density. To achieve sufficient optical power confinement to the core, higher doping of Ge_2O_3 was done to increase the refractive index. A nonlinearity constant of $20 \text{ W}^{-1}\text{km}^{-1}$ has been achieved by this method, which is eight times larger than that of the conventional DSF. This enables us to realize a sufficiently high conversion efficiency with a fiber length of 1 km. The other important issue is the polarization rotation within the fiber. To eliminate the polarization change, we further developed a polarization-maintaining, high-nonlinearity dispersion-shifted fiber (PM-HNL-DSF).¹⁷⁾ The fabricated PM-HNL-DSF has a nonlinear coefficient of $11 \text{ W}^{-1}\text{km}^{-1}$, a mode field diameter of $4.0 \mu\text{m}$, a zero-dispersion wavelength of 1567.0 nm ,



(a) Setup for PM-HNL-DSF measurement.



(b) Measured conversion efficiency

Figure 5

(a) Conversion efficiency measurement setup for PM-HNL-DSF wavelength converter.

(b) Measured dependence of conversion efficiency on the detuning between pump and signal wavelength.

and a dispersion slope of $0.032 \text{ ps/nm}^2/\text{km}$. The nonlinear coefficient is reduced by making the HNL-DSF polarization maintaining, however, the nonlinearity is still four times larger than that of the conventional fibers. The cross talk between the two polarization modes was -25 dB . The variance of λ_0 along the fiber was about $\pm 0.5 \text{ nm}$.

Figure 5(a) shows the experimental setup for measuring the conversion efficiency using a PM-HNL-DSF. **Figure 5(b)** shows the conversion efficiency in the FWM using the PM-HNL-DSF as a function of detuning between the pump wave and signal wave. The input pump power was 20.9 dB (123 mW). To eliminate the Brillouin scat-

tering effect, the pump power was modulated by a 1 MHz sinusoidal signal. A 3 dB conversion bandwidth of 72 nm with a flattened range of 66 nm was obtained. The bandwidth was limited by the phase matching condition.

4. Transmission and dispersion compensation experiment

4.1 Experiment using $\lambda/4$ -shifted DFB laser

By making use of the fact that the converted wave is the conjugate of the input wave, we can perform compensation of the chromatic dispersion and nonlinearity of a fiber. In actual applications to transmission systems, the polarization of the wave fluctuates in the optical fiber, so it is necessary to perform polarization diversity. The configuration shown in **Figure 6** was used to make the wavelength conversion insensitive to polarization.²⁾ The input wave is divided into two orthogonal polarizations using a polarization beam splitter. One of the beams has the same polarization as the lasing beam and is coupled to the DFB laser directly. The other beam is rotated by 90 degrees and coupled to the DFB laser from the opposite side of the cavity. The coupled beams cause FWM with a laser beam traveling in the same direction. The signals are combined to give an output which is insensitive to the polarization of the input signal. A transmission experiment

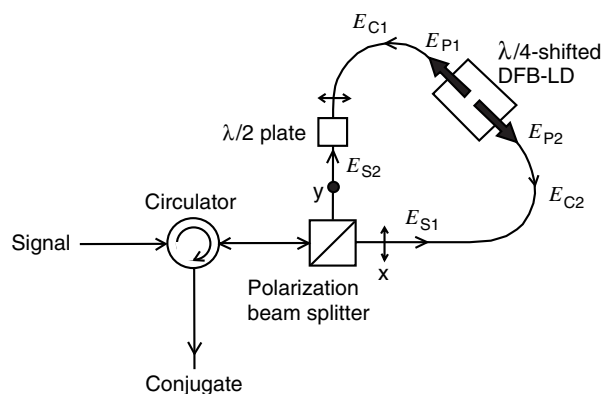
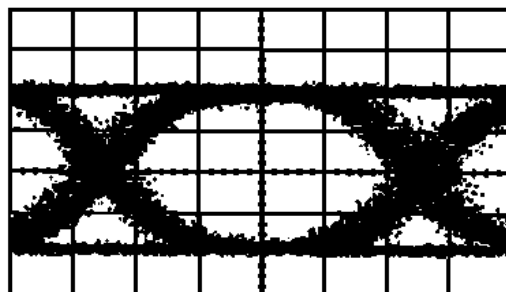


Figure 6
Configuration to make FWM in $\lambda/4$ -shifted DFB laser insensitive to input polarization.

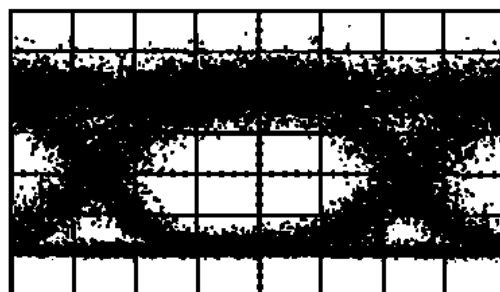
was done at 10 Gb/s using this diversity scheme. After 50 km of transmission in a single mode fiber (1.3 μm zero dispersion wavelength), the waveform was completely destroyed. We then performed a wavelength conversion with the detuning taken to be 2.5 nm. After wavelength conversion, an additional transmission of 50 km was performed. **Figure 7** shows the eye pattern before and after the transmission. Owing to the phase conjugation, the waveform was completely restored. The bit-error rate versus received power after 100 km transmission is shown in **Figure 8**. Floor free transmission was achieved. The penalty for the wavelength conversion was 0.6 to 0.8 dB for various polarizations. The total penalty after 100 km was 1.1 dB.

4.2 Experiment using PM-HNL-DSF

When compared with semiconductor-based four-wave mixing, FWM in an HNL-DSF (or PM-



(a) Before transmission



(b) After transmission

Figure 7
Eye pattern before and after 100 km transmission using $\lambda/4$ -shifted DFB laser phase conjugator.

HNL-DSF) has a symmetric and flat band conversion efficiency. This enables us to perform wavelength conversion for WDM signals. We have performed a simultaneous transmission and wavelength conversion experiment for 32 WDM channels.¹⁷⁾

Figure 9 shows our experimental setup.

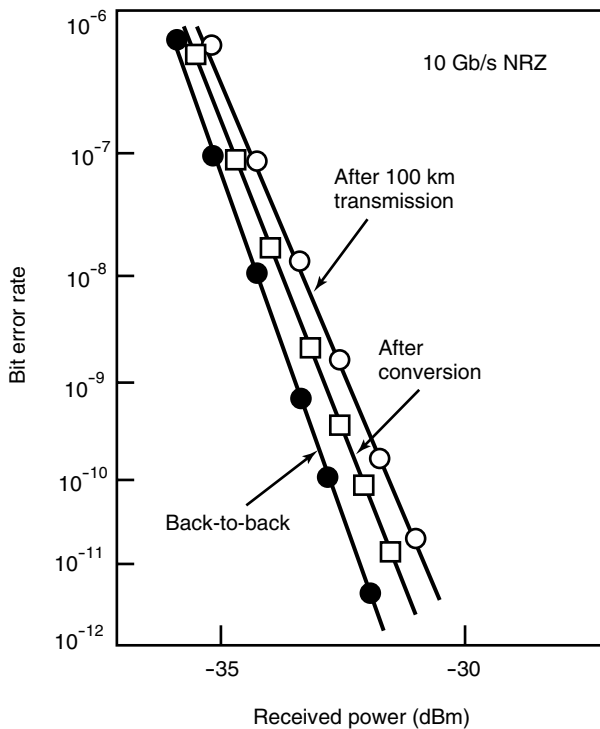


Figure 8
Bit-error rate characteristics of wavelength conversion and transmission using $\lambda/4$ -shifted DFB laser.

First, we examined the performance of the wavelength converter. An even and odd number of channels are bundled and modulated separately with a 10 Gb/s NRZ signal ($\text{PN}:2^{23}-1$) using an LiNbO_3 modulator. The channel spacing was 100 GHz (0.8 nm). After modulation, wavelength conversion was performed using the PM-HNL-DSF. To make the wavelength conversion insensitive to the polarization of the input signal, a loop configuration which operates on the same principle as the configuration shown in Figure 6 was employed. **Figure 10** shows the optical output spectrum just after the wavelength conversion. Signal wavelengths were up-converted simultaneously by FWM. The input power of the converter was -3 dBm/channel. At this input level, FWM crosstalk between channels was less than -30 dB. The difference in the conversion efficiency between channels was less than 2 dB. At the output of the converter, pump power was rejected using a band-stop filter with a 1 nm bandwidth and a rejection ratio of 35 dB. At the receiver, each channel was filtered by a bandpass filter with a bandwidth of 0.4 nm and detected after amplification by an EDFA. The bit-error rate characteristics are shown in **Figure 11** for channels 1, 8, 16, 24, and 32. All channels were converted with a power penalty of less than 2.6 dB.

Next, we performed a transmission experiment using a 1.3 μm zero dispersion fiber over 100 km with the wavelength converter placed mid-

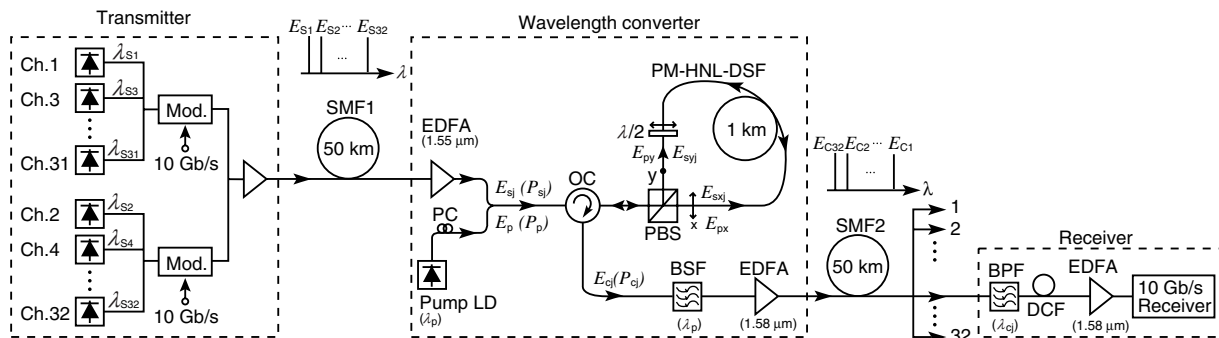


Figure 9
Experimental setup for 32 WDM channel wavelength conversion and transmission using PM-HNL-DSF wavelength converter.

way. Again, the bit-error rate characteristics for this experiment are shown in Figure 11. The total power penalty was less than 3.4 dB. Because of the phase conjugation using PM-HNL-DSF fiber, transmission of 320 Gb/s (32×10 Gb/s) over 100 km has been achieved.

5. Comparison of FWM in semiconductor gain medium and optical fiber

We have shown wavelength conversions in a $\lambda/4$ -shifted DFB laser and in an optical fiber (PM-HNL-DSF). **Table 2** compares the advantages and disadvantages of wavelength conversion using a $\lambda/4$ -shifted DFB laser and a PM-HNL-DSF. Wavelength conversion using a PM-HNL-DSF shows a much better performance, i.e., a flat conversion efficiency over a wide bandwidth and an efficiency that is symmetric with respect to the pump wavelength. This enables us to perform simultaneous wavelength conversion of WDM signals, as we have demonstrated. The disadvantage is that there is a restriction on the pump wavelength. It

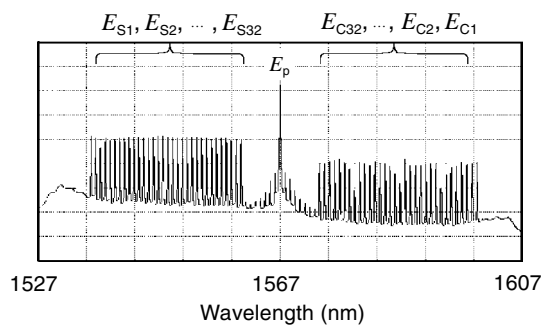


Figure 10
Output spectrum of the PM-HNL-DSF wavelength converter.
 E_{S1}, \dots, E_{S32} are converted to E_{C1}, \dots, E_{C32} .

Table 2
Characteristics of wavelength converters.

	Detuning dependence	Pump wavelength	Size
$\lambda/4$ -shifted DFB laser (or SOA)	Asymmetric conversion efficiency Small efficiency for large detuning	Arbitrary pump wavelength within the band	Small
PM-HNL-DSF	Flat conversion efficiency over wide bandwidth	Pump wavelength should be at zero dispersion wavelength	Bulky

must be adjusted to the λ_0 of the fiber to maintain phase matching.

Wavelength conversion to a desired wavelength by changing the pump wavelength is difficult. However, this may be improved to some extent by making the nonlinearity of the fiber much larger to enable wavelength conversion with a smaller fiber length. This will also help to make the bulky wavelength converter more compact. The advantage of wavelength conversion using a $\lambda/4$ shifted DFB laser or an SOA is that the device is very small in contrast to the bulky optical fiber. The small device size enables us to use an arbitrary pump wavelength to convert a wavelength to a desired one without being concerned with the phase matching condition. However, to do this we

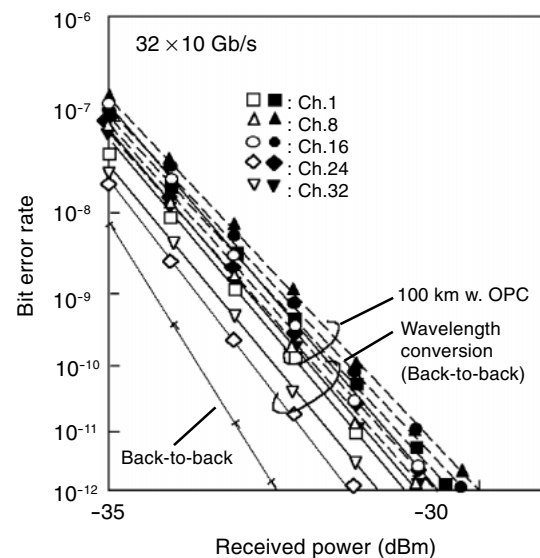


Figure 11
Bit-error rate characteristics of wavelength conversion and transmission using PM-HNL-DSF wavelength converter.

need a wavelength tunable pump laser, which as yet is a research target requiring intensive efforts.

The problem in FWM in a semiconductor gain medium is the non-flat and asymmetric conversion efficiency and the small conversion efficiency for a large detuning. This arises from the intrinsic mechanism of $\chi^{(3)}$ in the gain medium, as shown in Figure 1. However, efforts are now being made to improve this situation. One approach is to increase the $\chi^{(3)}$ for a large detuning. We have theoretically shown that the compressively strained quantum well gives a larger spectral hole burning component of $\chi^{(3)}$ than the conventional unstrained quantum well.¹⁸⁾ Further, there is a possibility of obtaining an almost symmetric and large conversion efficiency if we could use a quantum dot as a nonlinear medium.¹⁹⁾ The SOA integrated DFB laser also provides high-efficiency wavelength conversion.¹⁴⁾

Steps are now being taken to overcome the disadvantages of each type of wavelength converter by the introduction of new technologies.

6. Possible applications to photonic systems

Thus far, we have described wavelength conversion technologies using FWM. The present available technologies are still immature. However, there would be a variety of applications if we could fully realize the potential advantages of the FWM wavelength converter.

Figure 12 shows several possible system applications. Figure 12(a) is a phase conjugation optical network system in which subsystems are operated at different wavelengths and coupled using a phase conjugate wavelength converter. The phase conjugate wavelength converter performs the wavelength matching between subsystems and also enables long-distance transmission between nodes owing to the phase conjugation. The transmission line between subsystems could also be a WDM transmission line. Figure 12(b) shows an application to a bi-lateral transmission system. In such a system, we use

different wavelengths for the upward stream and downward stream. By introducing a wavelength

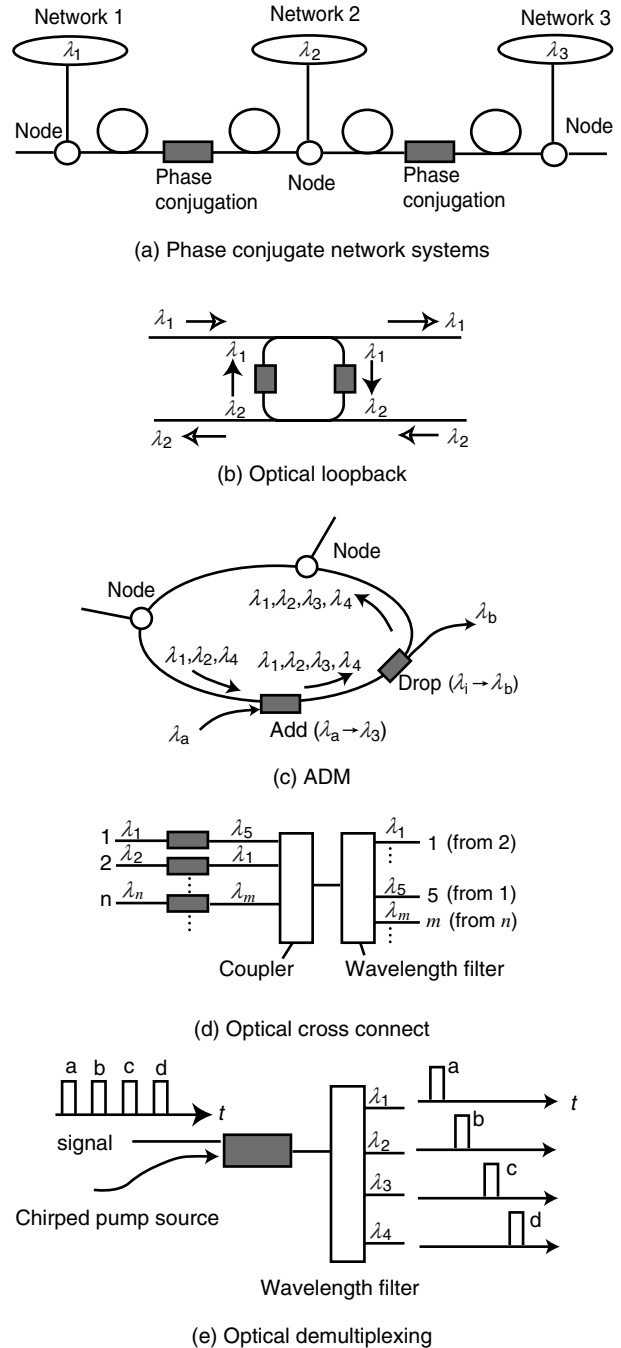


Figure 12
Possible system applications of wavelength converters. Shaded boxes are wavelength converters or combinations of wavelength converter and optical filter. (a) Phase conjugate network systems, (b) optical loop back in bi-directional transmission systems, (c) add-drop multiplexing (ADM) in WDM networks, (d) optical cross connect, and (e) optical demultiplexing.

converter, we can construct a simple optical loop back system.

The applications would further expand if we could realize a wavelength converter with a tunable pump laser. With the wide tuning range of the pump laser, we can convert to any wavelength within the transmission band. This enables us to apply the wavelength converter to the ADM of the optical signal in WDM systems. An example is shown in Figure 12 (c). Wavelengths of λ_1 , λ_2 , and λ_4 pass through the DFB laser type wavelength converter since it behaves just as an amplifier for the input signal. The input wavelength of λ_a is converted to λ_3 . Then, a signal is added to the network. Such a function can be realized with a DFB laser and an appropriate optical filter which eliminates unnecessary pump and conjugate waves. Similarly we can perform a drop action without affecting the signals in the network. An example of an optical cross-connect system is shown in Figure 12 (d). By combining wavelength conversion and filtering, we can perform optical cross connects by using the wavelength domain. Also, with a very fast response tunable pump source or a chirped pump source, we can perform demultiplexing of the high-bit-rate signals by using the wavelength domain as shown in Figure 12 (e). The results of several experiments of demultiplexing using FWM have been reported.^{3),4)}

7. Conclusions

We have reviewed various wavelength conversion technologies and presented our latest results for wavelength conversion using FWM, including those for a transmission and dispersion compensation experiment. We also glanced at possible applications of these wavelength conversion technologies. We have been pursuing FWM wavelength conversion because of the feasible advantage of its transparency, i.e., in contrast to the gating type wavelength conversion, the conversion could be insensitive to the modulation bit-rate and format. In all the applications in Figure 12, this transparency makes FWM wave-

length conversion highly advantageous over the gating type. However, there remains lots to be done to install FWM wavelength conversion in practical systems. In a DFB laser or an SOA-based FWM wavelength converter, the realization of flat bandwidth, the elimination of asymmetry, and a higher conversion efficiency are required. Efforts to improve this situation are under way, i.e., the introduction of compressive strain to the MQW,¹⁸⁾ use of quantum dots as a nonlinear medium¹⁹⁾, and the integration of a DFB laser with an optical amplifier.¹⁴⁾ The development of a tunable laser is a big issue for application to the optical cross connect, ADM, and demultiplexing of the TDM signal. As for fiber-based FWM, the biggest issue is to realize a still larger $\chi^{(3)}$ in the PM-HNL-DSF to make the converter smaller and obtain a better tolerance of the pump wavelength with respect to the zero dispersion wavelength of a fiber. A fiber length of several tens of meters, which is comparable to the EDFA, is desirable.

Development of a compact and simple converter with a high performance will open a wide area of applications in addition to the ones shown in Figure 12. We would like to continue our efforts towards this goal.

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