Recent Research and Development of All-Optical Wavelength Conversion Devices

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Abstract

Wavelength conversion is a key technology for flexible wavelength control in photonic networks. At optical cross-connect nodes in photonic networks, wavelength conversion decreases the channel blocking probability and makes it possible to reuse wavelengths. The efficient use of wavelength resources will accelerate the establishment of flexible networks. All-optical wavelength conversion is especially attractive because it does not need OE or EO devices and is independent of signal formats and bit rates, making photonic networks transparent with respect to these properties. This special issue focuses on the all-optical wavelength conversion devices being studied and developed at NTT Photonics Laboratories. This paper summarizes recent R&D progress on them.

1. Introduction

Broadband access networks are spreading and data rates of 100 Mbit/s to a single user in the home are becoming common. Considering the jump from bit rates of 64 kilobits to several megabits per second and now to 100 Mbit/s and the progress of popularization, Gbit/s-class transmission to a single user is not too far off. The increasing amount of communication traffic means more and more capacity is required in metropolitan/backbone networks. For this purpose, the introduction of wavelength division multiplexing (WDM) technologies has been accelerated. WDM technologies use the wavelengths of light and its application areas have been including point-to-point, rings with an add-drop function, and mesh networks with optical cross connects [1],[2]. This trend points to the need for the development of device/module technologies for routing, switching and optical signal processing through wavelength control. Especially important is the development of all-optical wavelength conversion devices, which accomplish wavelength routing without converting optical signals into electrical signals.

The five articles in this special issue describe all-optical wavelength conversion devices and their applications, as studied and developed in NTT Photonics Laboratories. This paper summarizes recent progress in our research and development of these wavelength conversion devices.

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2. Wavelength conversion technologies in photonic networks

In photonic networks, WDM and wavelength routing technologies allow optical signals to be routed as they are. At each node in such networks, wavelength conversion decreases the channel blocking probability and makes it possible to reuse wavelengths. The efficient use of wavelength resources will accelerate the establishment of flexible networks. Requirements for wavelength conversion devices are highly efficient conversion, a high bit rate, low noise, transparency to optical signal formats, and polarization insensitivity. Wavelength converters should also be cascadable, have a wide input power dynamic range, and operate using the same wavelength as the input one. When these requirements are met, wavelength conversion devices can be freely utilized within a network and at bridges between networks (Fig. 1).

Various wavelength conversion technologies have been developed, and they can be categorized into two types: i) the OE/EO type, where optical signals are converted to electrical signals and reconverted to optical signals of different wavelengths and ii) the all-optical type, where optical signals are directly converted to different wavelength signals [3],[4]. The advantage of the OE/EO type is that it can use conventional optical/electrical devices, such as laser diodes, photodiodes, and integrated circuits. However, the transparency with respect to signal format and bit rate is poor. On the other hand, all-optical wavelength converter technologies have excellent transparency to signal format and bit rate and are indispensable for the construction of photonic networks, where such transparency is very important. Table 1 summarizes the features of wavelength conversion technologies, and Fig. 2 maps the signal bit rates and conversion efficiency.

3. Recent research and development of all-optical wavelength converter devices

3.1 Two types of all-optical wavelength converter devices

Some all-optical wavelength converter devices are based on optical switching. The principle is that a signal light (wavelength λ1) drives an optical switch to

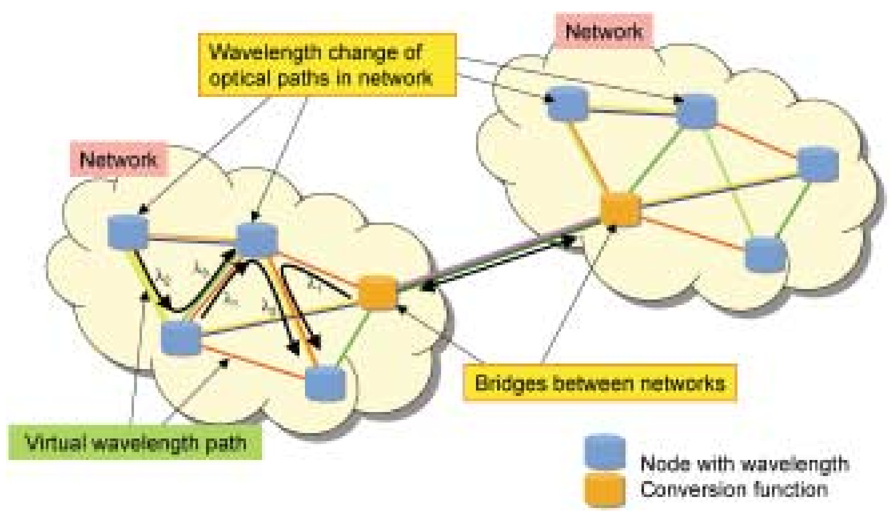

Fig. 1. Wavelength conversion technologies in photonic networks.

Table 1. Comparison of wavelength conversion technologies.

	OE/EO type	All-optical type				
		Optical switch type			Optical mixing type	
		Cross gain modulation (XGM)	Cross phase modulation (XPM)	Differential phase modulation (DPM)	Four wave mixing (FWM)	Difference frequency generation (DFG)
Typical devices	PD/IC/ LD(LD+MD)	SOA LD	SOA+ Mach-Zehnder interferometer	SOA+ Mach-Zehnder interferometer	Fiber SOA	QPM-LN*
Bit rate	~40 Gbit/s (IC dependent)	~40 Gbit/s (RZ→NRZ)	~40 Gbit/s	~160 Gbit/s	~1 Tbit/s	~1 Tbit/s
Bandwidth	Dependent on light source	Gain bandwidth (~30 nm)	Gain bandwidth (~30 nm)	Gain bandwidth (~30 nm)	~40 nm	~60 nm
Conversion efficiency	Excellent	Good	Good	Good	Fair	Fair
Polarization insensitivity	Excellent	Good	Good	Good	Fair	Fair
Input level	Receiver-dependent (~-17 dBm @10 Gbit/s)	-10 dBm @2.5 Gbit/s ~5 dBm @40 Gbit/s	-10 dBm @10Gbit/s ~8 dBm @40 Gbit/s	0~5 dBm @40 Gbit/s	~-20 dBm (SOA+DFB)	-15~5 dBm
Discrete/batch conversion	Discrete	Discrete	Discrete	Discrete	Batch available	Batch available
Issues	• Dependent on bit rate and format	• Chirp	• Narrow input dynamic range	• Narrow input dynamic range • Operation stability	• Low conversion efficiency • Polarization-dependent	• Low conversion efficiency • Polarization-dependent

∗QPM-LN: Quasi-Phase Matching $LiNbO_3$

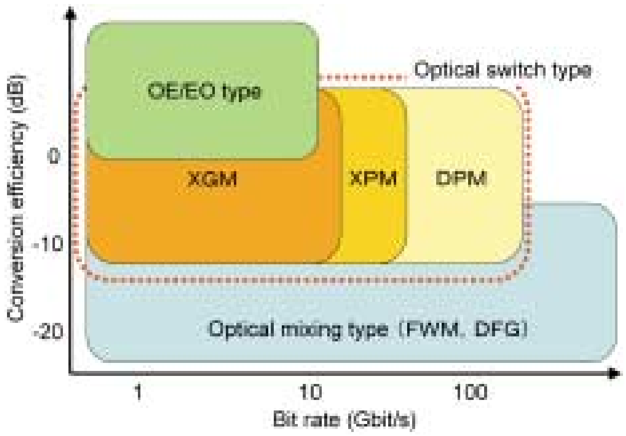

Fig. 2. Characteristics of wavelength conversion technologies.

convert the signal light to a different signal light (wavelength λ2) and the bit patterns of the former are copied to the latter. Optical switches that use the nonlinearity of a semiconductor gain medium have been actively studied.

Such semiconductor optical switches can use cross gain modulation (XGM), cross phase modulation (XPM), or differential phase modulation (DPM). The XGM types are based on a gate switch that utilizes the gain variation that occurs when a signal light changes the carrier density in a semiconductor optical amplifier (SOA). The XPM and DPM types are based on an interference switch that uses refractive index change. The merits of these wavelength conversion devices using SOAs include compactness, high conversion efficiency, and polarization insensitivity [4].

Other all-optical converters are based on optical mixing, the so-called coherent type. These make use of nonlinear effects in materials. When a signal light (wavelength λ1) and a pump light (wavelength λ2) are incident to a nonlinear material, a converted light (wavelength λ3) is generated. The most important methods of optical mixing are four-wave mixing (FWM) and difference frequency generation (DFG). They enable wavelength conversion at very high bit rates and simultaneous multi-wavelength conversion.

3.2 Optical switch types: Cross Gain Modulation (XGM)

In an XGM type, a signal light (wavelength λ1) decreases device gain due to saturation of the gain of an SOA that occurs when it is incident to an SOA and decreases the amplification ratio of a converted light (wavelength l2) (Fig. 3). Based on this principle, the bit patterns of the signal light and the converted light are reversed.

By utilizing a polarization-insensitive SOA, polarization-insensitive wavelength conversion can be achieved. The extinction ratio of XGM is still not large enough (about 10 dB). The input dynamic range is wide (7-10 dB). It was initially considered that the frequency characteristics were limited by a mechanism related to carrier lifetime in an SOA. However, XGM was found to involve a more complicated mechanism (described below) and higher bit rate operation than expected was observed. The factors that increase bit rate in XGM include reduction of carrier lifetime induced by a signal light and the filtering effect in an SOA. These factors have been clarified to be very effective for a long SOA with a high injection current. Over-40-Gbit/s operation by XGM has been reported [5], although this was accompanied by a change of the signal format from return-to-zero (RZ) to non-return-to-zero (NRZ). However, XGM has problems in that the output signal exhibits chirping and conversion efficiency is degraded when a signal light with a short wavelength is converted to one with a long wavelength.

3.3 Optical switch types: Cross Phase Modulation (XPM)

XPM is based on the principle that the phase modulation of the SOA in an interferometer causes a change in the interference state and switching so that the intensity of the converted light is modulated. The phase modulation of the SOA is a result of the refractive index change that occurs when the signal light induces carrier variation. Typical interferometers are the Michelson type and Mach-Zehnder type (Fig.4). An SOA as a phase modulator is principally set in one arm of an interferometer. However, for fine tuning of the interference state, in many cases, an SOA is placed in each of the two arms.

For XPM, the phase change of converted light passing through one arm in the interferometer should be set at π by controlling the intensity of the signal light

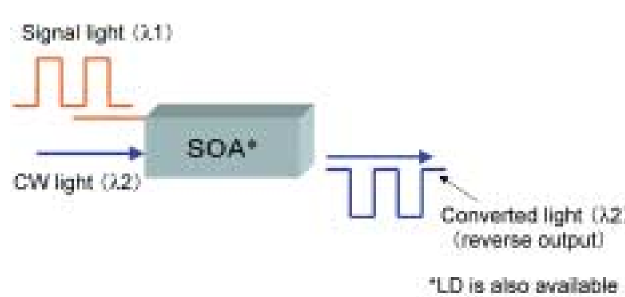

Fig. 3. Optical switch type: Cross gain modulation (XGM).

and converted light and the injection current to the SOA. The refractive index change necessary for XPM is induced by gain change of 3-4 dB in an SOA. Because the gain change for XPM is smaller than that for XGM, the chirp in wavelength conversion can be reduced. XPM also has a waveform reshaping effect because of the interferometer configuration. By using a polarization-insensitive SOA, polarization sensitivity in wavelength conversion can be reduced. By optimizing the device and input signal light conditions, we can accomplish wavelength conversion with an extinction ratio of over 15 dB and a high bit rate of 40 Gbit/s for an RZ signal. The wavelength range of wavelength conversion is about 30 nm, which is comparatively wide. For 10-Gbit/s-class NRZ signals, XPM wavelength converters have been developed for practical use by focusing on the reduction of input signal power, simplification of module assembly, and fabrication of units [6],[7].

This special issue introduced an XPM converter that uses planar lightwave circuit hybrid integration technology. The converter is hybrid integrated with an SOA and PLC.

Because XPM has an interferometer configuration, the characteristics of the wavelength converter depend on input signal intensity, and the dynamic range of input signal intensity is about 2-3 dB, which is comparatively narrow. To enlarge the dynamic range, a method in which an input level equalizer is placed at the input port of the wavelength converter has been proposed. XPM enables higher-bit-rate wavelength conversion than XGM. However, at 40 Gbit/s, the waveform of converted output signals degrades due to the limit of carrier relaxation time in an SOA.

3.4 Optical switch types: Differential Phase Modulation (DPM)

A DPM-type wavelength converter can overcome the bit rate limitation in the XPM wavelength converter. DPM is based on the following. Original signal and delayed signal are incident to the SOAs of XPM interferometer, so that the lights are phase-modulated at each SOA (Fig. 5).

This method cancels out the effect of slow carrier relaxation time in an SOA and enables high-bit-rate wavelength conversion and optical signal processing. So far, 40-Gbit/s wavelength conversion in the RZ format has been demonstrated using a semiconductor monolithic integrated device consisting of a symmetric Mach-Zehnder interferometer [8]. Wavelength conversion of 168 Gbit/s has also been observed using the delay loop method [9]. The bit rate for wavelength conversion has been remarkably increased through the development of ultrafast optical signal generation techniques.

For practical use, besides high bit rate operation, wavelength conversion to a light with the same wavelength as that of the signal light is important. In conventional wavelength conversion, the signal light (wavelength λ1) and the converted light (wavelength λ2) are divided by a filter at the output port. Therefore, when the wavelength of the signal light is the same as that of the converted light, filtering is not effective and conversion is difficult. To solve this problem, the signal light and the converted light can be filtered by changing the order of the transverse guided modes of the two lights [10]. In this method, it is necessary to control the guided modes of the signal and converted light exactly. Further improvement of the technique is required for stable operation.

A device including a parallel amplifier structure (PAS) has been proposed as a way to divide the signal and converted light [11]. In the PAS, SOAs are incorporated in both arms in a Mach-Zehnder interferometer. A semiconductor wavelength conversion device consisting of a Sagnac interferometer monolithically integrated with the PAS (Sagnac interfer-

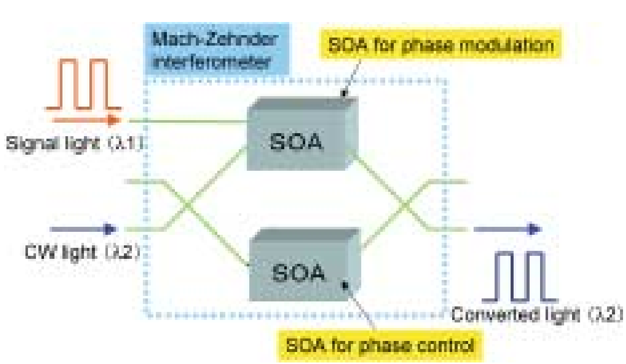

Fig. 4. Optical switch type: Cross phase modulation (XPM).

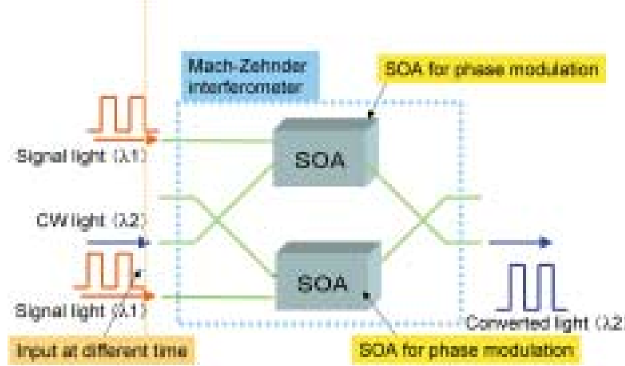

Fig. 5. Optical switch type: Differential phase modulation (DPM).

ometer with parallel amplifier structure (SIPAS)) has been proposed and demonstrated.

In a SIPAS, the signal light induces a refractive index change in an SOA of the PAS and phase modulation. After that, the signal light passes through the PAS and does not enter the Sagnac interferometer. The converted light is differentially phase modulated at the SOA of the PAS while circulating in the Sagnac interferometer so that the bit pattern of the signal light is copied to the converted light. The SIPAS device/module and its application are described in this special issue.

3.5 Optical mixing types: Four-wave mixing (FWM)

FWM uses the third-order nonlinearity of materials for wavelength conversion. When the signal light (frequency ω_i) and the pump light (frequency ω_p) are incident to a nonlinear material, the converted light (frequency $2\omega_p$-ω_i) is output (Fig. 6). An optical fiber [12] and an SOA [13] are typically used as nonlinear materials. FWM has good linearity and also enables wavelength conversion for 1-Tbit/s-class ultrafast signals. It also enables simultaneous conversion of multiple wavelengths. However, the conversion efficiency is low and decreases as the difference between the wavelength of the signal and pump lights increases. For higher conversion efficiency, a converter structure in which the SOA and a distributed feedback laser diode (DFB-LD) are monolithically integrated has been proposed. The structure does not need strong external pump lights. For practical use, the key issues are increasing efficiency, broadening the bandwidth, and reducing the polarization sensitivity.

3.6 Optical mixing types: Difference Frequency Generation (DFG)

DFG uses the second-order nonlinearity of materials for wavelength conversion. When the signal light (frequency ω_i) and pump light (frequency ω_p) are incident to a second-order nonlinear material, the converted light (frequency ω_p-ω_i) is output (Fig. 7). However, phase matching among the signal, pump, and converted lights is required for high conversion efficiency. Therefore, most of the devices for DFG have a periodic domain inversion structure for quasi-phase matching (QPM).

For highly efficient wavelength conversion, it is important to increase the length of the uniform QPM optical waveguide, improve the optical damage tolerance, and reduce polarization sensitivity [14]. Wavelength conversion by DFG can be done for Tbit/s-class signals. In addition, the wavelength bandwidth is wide, the wavelength conversion range is large, and multiple wavelengths can be converted simultaneously. DFG devices that use QPM $LiNbO_3$ are described in this special issue.

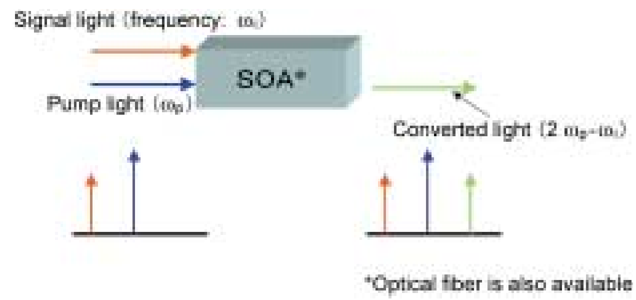

Fig. 6. Optical mixing type: Four wave mixing (FWM).

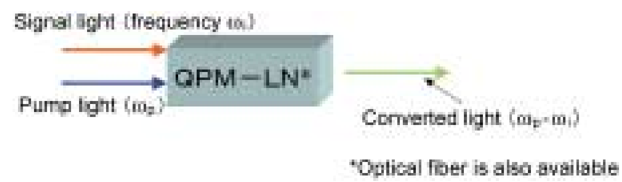

Fig. 7. Optical mixing type: Difference frequency generation (DFG).

4. Conclusion

All-optical wavelength conversion devices were overviewed. All-optical wavelength conversion technologies provide transparency to signal format and bit rate and are promising for constructing photonic networks. Hereafter, besides the development of fabrication technology for modules and units, increased efficiency, stability, and operability are necessary for practical use. All-optical wavelength converter devices perform not only wavelength conversion but also high-grade optical signal processing. The wavelength conversion technologies described here should lead to the creation of photonic networks.

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