Wavelength Conversion Technologies for WDM Network Applications

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(Invited Paper)

***Abstract*—WDM networks make a very effective utilization of the fiber bandwidth and offer flexible interconnections based on wavelength routing. In high capacity, dynamic WDM networks, blocking due to wavelength contention can be reduced by wavelength conversion. Wavelength conversion addresses a number of key issues in WDM networks including transparency, interoperability, and network capacity. Strictly transparent networks offer seamless interconnections with full reconfigurability and interoperability. Wavelength conversion may be the first obstacle in realizing a transparent WDM network. Among numerous wavelength conversion techniques reported to date, only a few techniques offer strict transparency. Optoelectronic conversion (O/E–E/O) techniques achieve limited transparency, yet their mature technologies allow deployment in the near future. The majority of all-optical wavelength conversion techniques also offer limited transparency but they have a potential advantage over the optoelectronic counterpart in realizing lower packaging costs and crosstalk when multiple wavelength array configurations are considered. Wavelength conversion by difference-frequency-generation offers a full range of transparency while adding no excess noise to the signal. Recent experiments showed promising results including a spectral inversion and a 90 nm conversion bandwidth. This paper reviews various wavelength conversion techniques, discusses the advantages and shortcomings of each technique, and addresses their implications for transparent networks.**

I. Introduction

TELECOMMUNICATIONS is currently undergoing a large-scale transformation. Multimedia services, HDTV, and computer links in the national information highway will undoubtedly benefit us by improving the way of life and increasing efficiency. Such new aspects of telecommunications will rapidly increase the communication traffic, which will in turn demand a national network that can accommodate the entire traffic in a cost effective manner. Single-mode fibers deployed in the public telecommunications network today can potentially accommodate more than 1 Tb/s traffic. Such enormous bandwidth is by far underutilized by even a top-of-the-line telecommunication system (2.5 Gb/s) commercially available today. Higher bit-rate systems at 10 Gb/s are becoming available, however, the dispersion and nonlinearities in the fiber severely limit the transmission distance. Wavelength division multiplexing (WDM) techniques offer a very effective utilization of the fiber bandwidth directly in the wavelength domain, rather than in the time domain. In addition, wavelength can be used to perform functions as routing and switching [1], which becomes an important consideration for realization of an all-optical transparent network layer in the network [2].

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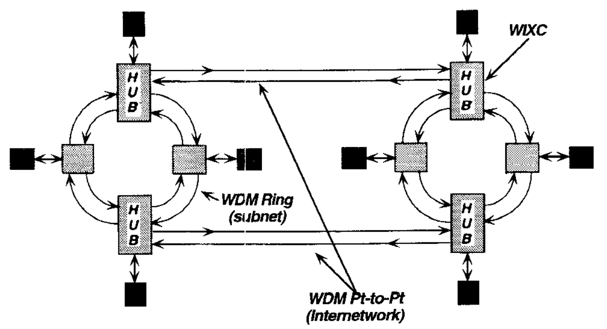


Fig. 1. WDM networks where wavelength interchanging cross-connects (WIXC) are utilized. The two WDM ring subnetworks are connected to each other by four HUB's which include WIXC's (courtesy of [6]).

The number of wavelengths in WDM networks determines the number of independent wavelength addresses, or paths. Although this number may be large enough to fulfill the required information capacity, it often is not large enough to support a large number of nodes. In such cases, the blocking probability rises due to possible wavelength contention when two channels at the same wavelength are to be routed at the same output. One method of overcoming this limitation is to convert signals from one wavelength to another [3]. Fig. 1 illustrates one arrangement for using wavelength conversion for interconnecting WDM networks. This example contains four wavelength interchanging cross-connects (WIXC) and a common network control to permit their dynamic rearrangeability. The WIXC contains space switches and wavelength converters to route signals from any wavelength of any input port to any wavelength of any output port.

The benefit of wavelength conversion varies with network architectures and traffic patterns [4]–[6]. A "small" network with a fixed traffic pattern may not need wavelength conversion and maintain a low blocking rate. A "large" network with dynamic traffic patterns will greatly benefit from wavelength conversion. It is generally accepted that the benefit of wavelength conversion increases with increased traffic.

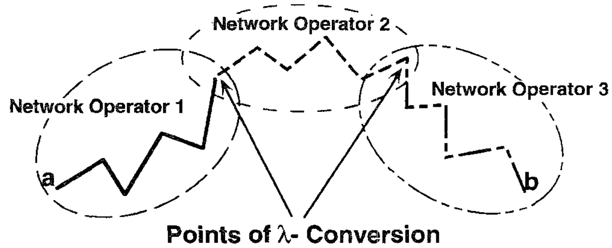


Fig. 2. Distribution of network control and management into smaller subnetworks utilizing wavelength conversion. Network operators 1, 2, and 3 are responsible for their own subnetworks and wavelength assignments within the subnetworks are independent of each other (courtesy of [6]).

Wavelength conversion also allows distributing the network control and management into smaller subnetworks and allows flexible wavelength assignments within the subnetwork. Fig. 2 illustrates this effect. Network operators 1, 2, and 3 are required to manage their own subnetworks, and wavelength conversion may be needed for communication between the subnetworks.

For WDM networks to accommodate vast users and evolve in the future, maximum degrees of transparency and interoperability [7] are desired. In addition, transparent networks facilitate implementations of sophisticated security architectures. The first obstacle in achieving transparency in WDM networks lies in wavelength conversion. The majority of wavelength conversion methods offer only limited transparency. This paper reviews various wavelength conversion techniques, discusses the advantages and shortcomings of each technique, and addresses their implications for transparent networks.

II. Wavelength Converters-Comparison Issues

Wavelength converters reside in two sectors of the network: WIXC's and wavelength adapters. A WIXC is a network element which cross-connects nodes with wavelength conversion when needed [8]. A Wavelength Adapter is an element that changes a noncompliant wavelength to a compliant wavelength. Here, compliant wavelengths are defined as a specific set of wavelengths used in the multiple wavelength optical network. The need for wavelength adaptation disappears once all network elements are based on a set of standard compliant wavelengths. We will limit our discussions to wavelength conversion in WIXC.

There are countless issues to be considered in comparing wavelength conversion techniques. Table I lists some of the key comparison issues. These issues are grouped in three large categories: signal quality, configuration, and performance. *Signal quality* includes signal-to-noise ratio, chirp, amplitude distortion, and extinction ratio, and largely determines the bit-error-rate and the cascadability of wavelength converters. *Configuration* is related to the actual implementation of the wavelength conversion in the WIXC, and is closely linked to the mapping function of the wavelength converter and the resulting WIXC architecture. This category includes control requirements, dynamic ranges of input signals, polarization dependence, filtering requirements, and wall-plug power requirements. Lastly, the *performance* includes conversion

TABLE I
Wavelength Converter Comparison Issues

	COMPARISON ISSUES	COMMON ISSUE
signal quality	s/n ratio	wavelength registration
	chirp	
	amplitude distortion	
	extinction ratio	
configuration	WIXC architecture	
	control and stability	
	polarization dependence	
	optical filtering	
	dynamic range of input signal	
	wall-plug power requirement	
performance	conversion efficiency	
	conversion bandwidth	
	bit-rate-limit and dependence	
	transparency	

efficiencies, conversion bandwidths, and bit-rate (or signal bandwidth) limits. In contrast to these comparison issues, all wavelength converters, regardless of what mechanism is used, must accurately register wavelengths. As we will discuss later in this paper, some of the above comparison parameters are inter-related with each other. For instance, a semiconductor optical amplifier wavelength conversion bandwidth limit is 1 Gb/s for probe power levels at -10 dBm [9], but 20 Gb/s is possible for probe power levels at 4 dBm [10], [11], [60]. Another example is conversion efficiency and noise figure. Some wavelength conversion methods offer a high conversion efficiency at the expense of a high noise figure and high wall-plug power. Wall-plug power can be an important criterion in a large WIXC where total power requirements can add to a very high value and back-up power becomes critical.

Characteristics of an ideal wavelength converter are obvious. In absence of such an ideal element, it is important to balance out the advantages and disadvantages according to the application and extent of the network. Among the issues discussed above, the required level of transparency, the minimum signal-to-noise ratio, and the preferred WIXC architecture are significantly different depending on the network applications.

It is the objective of this paper to consider wavelength converters as black boxes, list the parameters and discuss the tradeoffs. The black box includes all essential elements for wavelength conversion. The black box will have two optical ports for input and output signals, a power connection, and a control interface. Components such as pump or probe lasers will be included in the box, but no regenerators will be included. Filtering requirements will be included and we will make qualitative comparisons. The wall plug power is defined as a total dc power required to operate the entire box. Conversion efficiency is defined as a ratio of the output signal power with respect to the input. Table II summarizes the comparison of wavelength conversion techniques in light of the comparison issues discussed above. Section III overviews three categories of wavelength conversion mechanisms and

TABLE II
COMPARISON OF VARIOUS WAVELENGTH CONVERSION TECHNIQUES

	Optoelectronic Conversion	Cross-gain-modulation in semiconductor amplifiers	Cross-phase-modulation in semiconductor amplifiers	Four-wave-mixing in semiconductor amplifiers	Difference-frequency-generation in semiconductor waveguides
mapping function between input, output, and probe	$\omega_{\text{output}} = \omega_{\text{transmitter}}$	$\omega_{\text{output}} = \omega_{\text{probe}}$	$\omega_{\text{output}} = \omega_{\text{probe}}$	$\omega_{\text{output}} = 2\omega_{\text{pump}} - \omega_{\text{in}}$	$\omega_{\text{output}} = \omega_{\text{pump}} - \omega_{\text{in}}$
signaling category	variable-input-fixed-output	variable-input-fixed-output	variable-input-fixed-output	variable-input-fixed-output	variable-input-fixed-output
transparency	limited	limited	limited	strict	strict
s/n ratio	noise Fig. 7–9 dB s/n > 40 dB if regen.	noise Fig. 7–9 dB	noise figure ~3 dB	s/n < 20 dB	same as input signal s/n ratio
extinction ratio	~10 dB for direct ~20 dB for ext.mod	~8 dB	~15 dB	approximately same as input	same as input
amplitude distortion	mostly digital response	large distortion due to carrier density fluctuation	mostly digital response	negligible for detuning >10 GHz	none
chirp parameter	~3 for direct modulation ~0.3 for electro absorption –1 for Mach–Zehnder mod.	4 for bulk amplifier (for polarization insens. operation) 2.5 for QW amp. (pol. sens. operation)	−0.7~0.4 (depends on the interferometer splitting ratio and inversion of logic)	chirp reversal	chirp reversal
polarization sensitivity	insensitive	sensitive unless critical design is incorporated	sensitive unless critical design is incorporated	sensitive insensitive for multiple pumps	insensitive, polarization diversity possible
optical filtering	not needed	must filter strong input signal	not needed for counter-propagating geometry	must filter strong pump and satellite wavelength	pump filtering trivial. input signal must be filtered.
dynamic range of input signal	17 dB (−17 dBm to 0 dBm for 10 Gb/s)	input power > 0 dBm for 10 Gb/s	3 dB for Extinction Ration > 12 dB	> 10 dB	> 40 dB
wall-plug power	2 W for directly modulated OC-192 6 W for externally modulated OC-192	~200 mW	~200 mW (for pol. sens. QW) ~500 mW (for pol. insens. bulk)	~150 mW	~300 mW
conversion efficiency	17 dB for OC-192	8 dB for OC-192	-2 dB for OC-192	-7 dB	-4 dB (theory) -17 dB (experiment)
conversion bandwidth (3 dB)	extremely broad (limited by the detector)	$\|\omega_{\text{input}} - \omega_{\text{center}}\| < 2^*\pi^*$ (3 THz	$\|\omega_{\text{input}} - \omega_{\text{center}}\| < 2^*\pi^*$ (2 THz)	$\|\omega_{\text{input}} - \omega_{\text{center}}\| < 2^*\pi^*$ (1 THz)	$\|\omega_{\text{input}} - \omega_{\text{center}}\| < 2^*\pi^*$ (12 THz)
bit-rate-limit	~10 Gb/s	~10 Gb/s	~10 Gb/s	> 10 Gb/s	> 10 Tb/s
advantages	• ready for deployment. • regen. improves s/n ratio	• simple configuration • gain in conv. eff.	• reduced chirp, distortion	• chirp reversal • transparent	• chirp reversal • transparent • no excess noise •broad bandwidth
disadvantages	• cost increases with bit-rate and with number of elements • limited transparency	• high noise figure, distortion, and chirp. • limited transparency	• narrow dynamic range of input power • limited transparency	• large spontaneous noise • narrow conversion bandwidth	• phasematching has to be achieved by careful fabrication.
References	21, 22 (components only)	9, 10, 11, 35, 36, 37, 38, 60	39, 40, 41, 42, 43, 44	47, 48, 49, 50, 51, 53	15, 54, 55, 56

Section IV makes detailed comparisons of techniques from each category.

III. Wavelength Conversion Mechanisms

This section briefly overviews three categories of wavelength conversion mechanisms. Inside the black-box, the core of the wavelength converter is in general a three terminal device consisting of input, output, and control terminals. Fig. 3(a) is a functional block diagram of a general wavelength converter. Depending on the mapping functions and the form of control signals, wavelength converters can be classified into three categories: optoelectronic, optical gating, and wave-mixing. Fig. 3(b)–(d) shows functional block diagrams for the three types of wavelength converters. There are also other ways of classifying wavelength converters. Depending on the signal routing mechanisms, they are classified as optoelectronic wavelength converters and all-optical wavelength converters. They can also be classified according to the signal properties: a variable-input-fixed-output converter, a variable-input-variable-output converter, and a fixed-input-variable-output converter. The following subsections describe

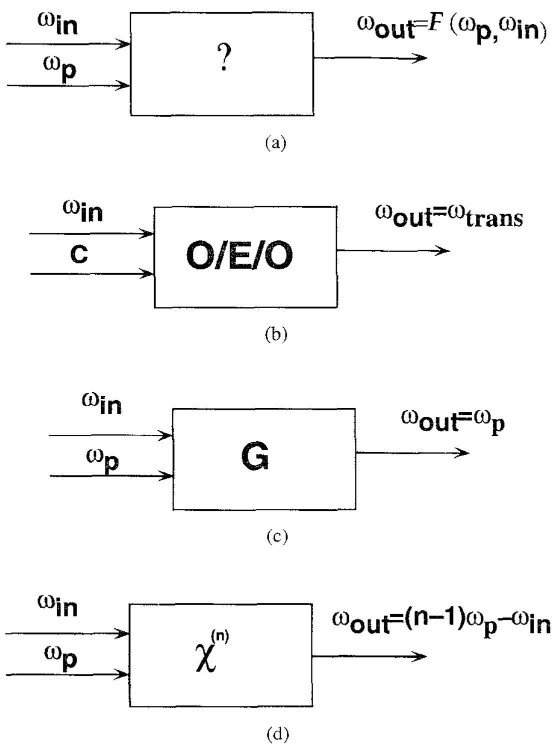


Fig. 3. (a) A functional block diagram of a general wavelength converter. Functional block diagrams of (b) optoelectronic, (c) optical gating, and (d) wave-mixing (e.g., difference-frequency-generation) wavelength converters.

the three categories according to the first classification method, and Section IV compares wavelength conversion mechanisms in more detail.

A. *Optoelectronic (O/E–E/O) Wavelength Conversion*

Most straightforward of all wavelength conversion techniques is a detection of the optical signal and a retransmission of the signal (O/E–E/O). For example, a commercially available SONET repeater with or without a regenerator is an O/E–E/O wavelength converter, provided that the output wavelength is a compliant wavelength. This technique involves an electrical routing of the signal during the wavelength conversion process. This is a variable-input-fixed-output wavelength converter, unless a tunable laser or a laser array is used.

B. *Optical Gating Wavelength Conversion*

A large number of wavelength converters fall into this category. This type of wavelength converter employs an optical device which changes its characteristics depending on the intensity of the input signal. This change is monitored by a cw signal called probe and this probe signal will contain the information in the input signal. There are countless wavelength conversion methods that fall into this category, resulting from the fact that there are numerous optical gating mechanisms available. This category includes semiconductor optical amplifier cross-gain modulation, semiconductor optical amplifier cross-phase modulation, semiconductor lasers with saturable absorption, and nonlinear optical loop mirrors. This is a classical example of variable-input-fixed-output wavelength converters, and we will see more of these wavelength conversion methods as more optical gating methods are utilized.

C. *Wave-Mixing Wavelength Converters*

Perhaps the least explored but offering the highest degree of transparency is wavelength conversion based on wave-mixing. In a broad sense, this category includes optical-acoustic wave-mixing [12], optical-electrical wave-mixing [13], as well as nonlinear optical wave-mixing. The first two can be quite effective frequency translation methods for dense FDM, however, they are unlikely to provide larger frequency translation required for WDM. The nonlinear optical wave-mixing results from nonlinear interactions among the optical waves present in a nonlinear optical material. This mechanism is sensitive to both amplitude and phase information, and is the only category of wavelength conversion methods that offers strict transparency. So far, four-wave-mixing based on the third-order optical nonlinearity and difference-frequency-generation based on the second-order optical nonlinearity have been demonstrated. The utilized mixing functions are parametric, and the mapping functions allow one-to-one mapping of an input wavelength to an output wavelength. Therefore, the conversion process is variable-input-variable-output. One unique feature common to this category of wavelength converters is that they allow simultaneous conversions of multiple input wavelengths to multiple output wavelengths. This property is an outcome of the superposition properties of optical fields. The details of this process are discussed in [14] and [15], and are briefly summarized in the later section.

IV. Comparison of Wavelength Converters

This section compares wavelength conversion techniques in more detail.

A. *Optoelectronic (O/E–E/O) Wavelength Conversion*

Optoelectronic wavelength conversion can be achieved in an optical repeater with or without signal regeneration. It is even possible to undertake the entire WIXC functionality by combining an electronic cross-connect with an optoelectronic repeater. The optoelectronic wavelength conversion technology is more mature and is more readily applicable to field deployment when compared to all-optical counterparts. In addition, the possibility of regeneration of signal and the added capability of network control and management make this approach extremely attractive. The O/E–E/O operation also accommodates wide optical power levels and requires no filtering or polarization control. On the other hand, there are shortcomings associated with this technique, and we will discuss them below.

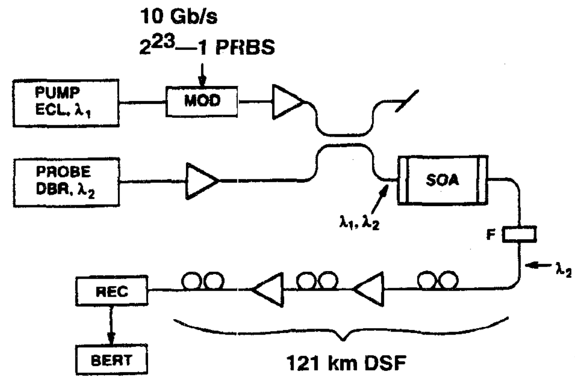
Currently, full 3R-regeneration (retiming, reshaping, reclocking) is typically performed after every 40 km. However, optical fiber amplifiers are rapidly replacing the regenerators that are already in place today. Transoceanic distance (>9000 km) transmission without regeneration has already been demonstrated by numerous research groups. Due to high cost, low reliability, and poor upgradability, most network operators hope to avoid regeneration unless it is really necessary. For consistent comparisons of wavelength conversion techniques, we will continue our discussions with optoelectronic wavelength conversion without regeneration.

The first limitation of this technology lies in limited transparency. The information in the form of phase, frequency, and analog amplitude is lost during the conversion process. The highest degree of transparency that the optoelectronic conversion can achieve is digital transparency, where digital signals of any bit-rates up to a certain limit are accommodated. The operation bandwidth must cover those of all anticipated applications. The gain-bandwidth limitations, on the other hand, dictates that the performance of the optoelectronic repeater can not be optimized for all bit-rates. Usually, optimizations are made for the high end bit-rate, and the sensitivities at lower bit-rates will deviate from their optimum values.

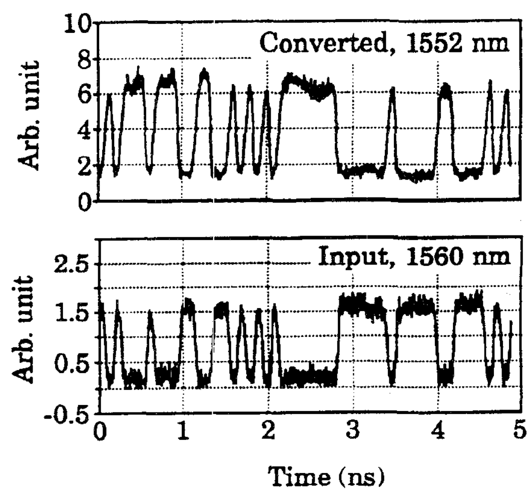
An optoelectronic wavelength converter consists of a receiver and a transmitter. At the physical level, this is equivalent to a detector, an RF amplifier, and a laser. It is worth noting that RF amplifiers increase the conversion efficiency (defined as a power ratio between the converted signal and the input signal) at the expense of the signal-to-noise ratio. The ratio of signal to noise ratio before and after amplification is defined as a noise-figure [16]. Numerous wavelength converters employ either electrical or optical amplification during the conversion process. Some amplifiers outperform others in terms of noise figures and power requirements. Noise figures as low as 3.1 dB [17] are demonstrated in 980 nm pumped Erbium-doped fiber amplifiers (EDFA), whereas those of broadband RF and semiconductor optical amplifiers lie in the 7–9 dB range [18]–[20]. It is important to note that a combination of an EDFA with a noise figure of 4–5 dB and an all-optical wavelength converter with no excess noise can outperform a typical optoelectronic wavelength converter in numerous categories, including the signal-to-noise ratio and the conversion efficiency.

In terms of wall plug power, high-speed electronics require a constant power supply at high levels to achieve high speed and high gain. The wall plug power required for the 2.5 Gb/s repeater consisting of a receiver front-end, an RF amplifier, and a transmitter is approximately 2 W [21], and is anticipated to be at least double for 10 Gb/s. The power requirement is more severe for a system with an external modulator. This power requirement is higher than those for the majority of all-optical wavelength conversion technologies. For instance, the semiconductor optical amplifier cross-gain modulation wavelength converter which requires a -5 dBm probe signal and a 100 mA constant current translates to approximately 200 mW wall-plug power requirement. However, one should also consider the fact that the optoelectronics system achieves much higher conversion efficiency (gain). The amplification factor or conversion efficiency of an optoelectronic converter is typically 30 dB for 2.5 Gb/s systems and 17 dB for 10 Gb/s systems, whereas the cross-gain modulation wavelength converter offers 10 dB at 2.5 Gb/s and 5 dB at 10 Gb/s.

Another key consideration in comparing optoelectronic versus all-optical wavelength conversion methods is cost. An 2.5 Gb/s optoelectronic wavelength converter realized by combining a receiver and a transmitter costs approximately U.S. $9000 [22]. This is approximately the same as the cost of a polarization insensitive semiconductor amplifier capable



(a)



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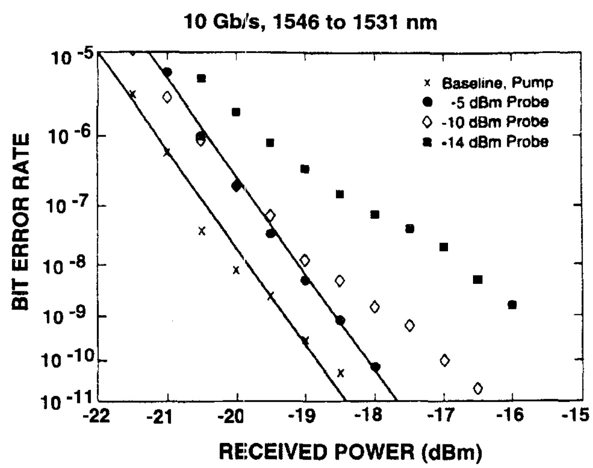


(c)

Fig. 4. (a) A configuration for a cross-gain modulation semiconductor optical amplifier wavelength converter (courtesy of [10]), (b) bit patterns of input and output signals (courtesy of [11]), and (c) bit error rate for 10 Gb/s operation (courtesy of [10]).

of wavelength conversion at 10 Gb/s (~U.S. $10 000) [23]. Although the unit costs are similar in two cases, there are two factors that can eventually make the optoelectronic wavelength converter more costly. The first factor is the market. Since the optoelectronic market is far greater than the other, the cost of the semiconductor amplifier may significantly drop if its market grows to become similar in size. The second is packaging cost. A WIXC will require multiple wavelength converters, and packaging them in an array configuration can significantly reduce the packaging cost per unit converter. This packaging is not as trivial in optoelectronic wavelength converters as in all-optical counterparts because of a strong RF coupling which causes crosstalk. High-speed electronics require sophisticated packaging to avoid crosstalk from other channels. There are a number of groups making effort toward multichannel optoelectronic packaging with low crosstalk and we look forward to good system results.

The robust operation and mature technologies associated with this technology make the optoelectronic wavelength converter attractive for nontransparent WDM network applications.

B. Optical Gating Wavelength Conversion

This category of wavelength converters is very similar to the optoelectronic wavelength converter in terms of its limited transparency and thresholding characteristics [24]. The technologies discussed in this section are far less mature than the optoelectronic method discussed in the previous section. If this category of converters are favored over the optoelectronic ones, it would be due to cost and packaging considerations as discussed above.

The optical gating function is achieved predominantly by the third-order optical nonlinearity of the material. The magnitude of the optical nonlinearity determines the input signal power required to gate the probe signal for wavelength conversion. The materials available today have extremely small third order nonlinearities unless resonant enhancement is used. The problem of resonant nonlinearity is that it is accompanied by resonant absorption and that the resonant transition lifetime limits bit rates. On the other hand, a long interaction length must be used for relatively weak nonresonant nonlinear effects to accumulate.

Saturable absorption provides a relatively simple and compact realization of wavelength conversion [25]–[29]. The input signal saturates the absorption of exciton transitions near the bandgap and allows the probe beam to transmit. This technique showed a bandwidth limit of 1 GHz due to carrier recombinations, and suffered from a bistable behavior when integrated with lasers. Similar optical gating wavelength conversion can be obtained by utilizing gain-suppression mechanism in semicondutor lasers such as tunable DFB lasers [30], Y-Lasers [31], and T-Gate Lasers [32]. The gain suppression mechanism can achieve higher bit-rates than saturable absorption owing to stimulated emission inside the gain material. A recent work reported 10 Gb/s wavelength conversion in a DBR structure [33]. Similarly, cross-gain modulation in semiconductor optical amplifier can also achieve 10 Gbit/s or even higher bit rates [10], [60]. The mechanisms discussed so far in this section suffer relatively large phase modulation in the signal during the gain or absorption modulation. This phase modulation adversely affect transmission capabilities through the conventional single mode fibers. One of the most successful conversion demonstrations is achieved in a semiconductor optical amplifier utilizing cross-phase modulation. Typically, a Mach–Zehnder interferometer is used for converting the phase modulation within one of the arms to an intensity modulation at the output. This is discussed in detail in Section IV-B2). Last, a recent demonstration of a nonlinear-optical-loop-mirror is an example of accumulating a weak nonresonant nonlinear optical effect over a long interaction length. This was made possible in a silica fiber with a propagation loss below 0.3 dB/km. The following sections discuss the details of selected devices.

1) Cross-Gain Modulation in Semiconductor Optical Amplifiers: The gain in a semiconductor optical amplifier saturates as the optical power level increases. Therefore, it is possible to modulate the amplifier gain with an input signal, and, in turn, encode this gain modulation on a separate cw probe signal traveling through the amplifier at another wavelength. Fig. 4(a) illustrates this configuration. As in saturable absorber type wavelength converters, the saturation is never complete, and the extinction ratio of the converted signal is typically below 8 dB. Fig. 4(b) shows the bit patterns of input and output signals. The advantage over the saturable absorption technique is its capability to operate beyond the spontaneous recombination rate of carriers. The presence of the optical probe signal induces stimulated emission which results in reduction of the carrier lifetime. These wavelength converters are polarization dependent due to polarization dependent gain and confinement factors. By utilizing semiconductor amplifiers with bulk or strain-compensated active regions [34], the polarization dependence is greatly reduced. References [35] and [36] discuss polarization independent wavelength conversion at 10 and 20 Gb/s for probe signal powers up to -5 dBm and 3 dBm. Fig. 4(c) shows 10 Gb/s bit-error-rate measurements obtained in [10]. The conversion experiment show a 1 dB penalty for -5 dBm probe power. One of the key shortcomings of this method is a signal-to-noise deterioration due to a large spontaneous emission background. Typical noise figures of semiconductor amplifier are 7–8 dB. Usually, the conversion efficiency is lower than the gain, and the noise figure for the conversion process is even higher than the intrinsic noise figure of the amplifier [20]. In addition, the signal quality further deteriorates with chirping and amplitude distortion caused by carrier modulations. Experiments discussed in [37] show nearly 2 dB dispersion penalty at 6 Gb/s over 20 km of conventional single mode fiber. Two stage cascaded wavelength conversion showed approximately 5 dB power penalty and pulse reshaping [38]. Despite some of shortcomings in signal quality, this is one of the simplest wavelength conversion methods which utilizes a component available today.

2) Cross-Phase Modulation in Semiconductor Optical Amplifiers: Optical signals traveling through semiconductor optical amplifiers undergo a relatively large phase modulation compared to the gain modulation. This is manifested

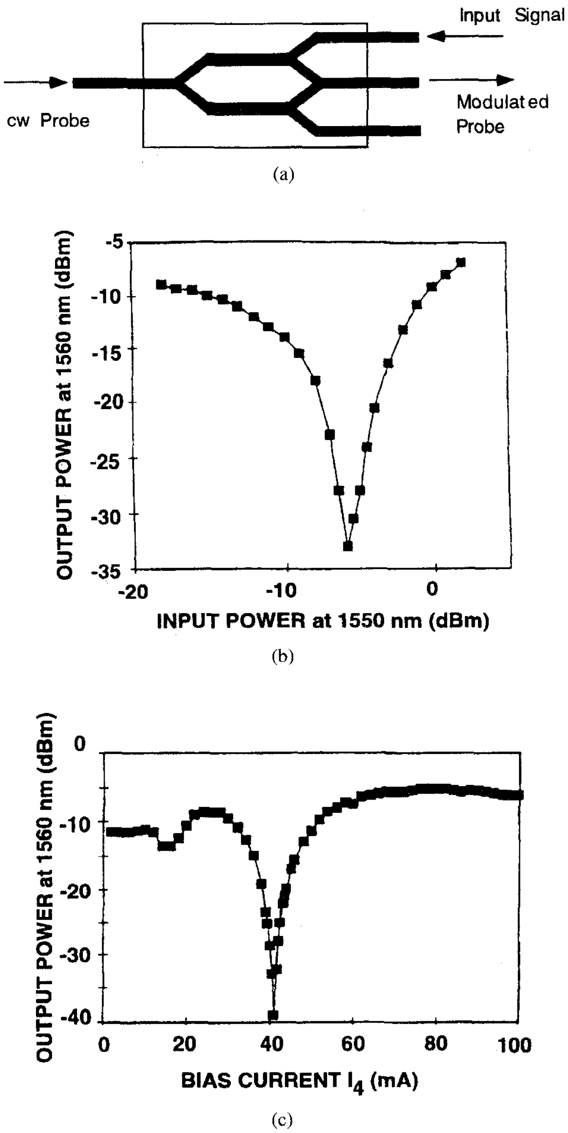


Fig. 5. (a) A Mach–Zehnder configuration for a cross-phase modulation semiconductor optical amplifier wavelength converter, (b) the output power dependence on the input power for a cross-phase modulation semiconductor optical amplifier wavelength converter (courtesy of [43]), and (c) the output power dependence on the input current into one of the arms of a cross-phase modulation semiconductor optical amplifier wavelength converter (courtesy of [43]).

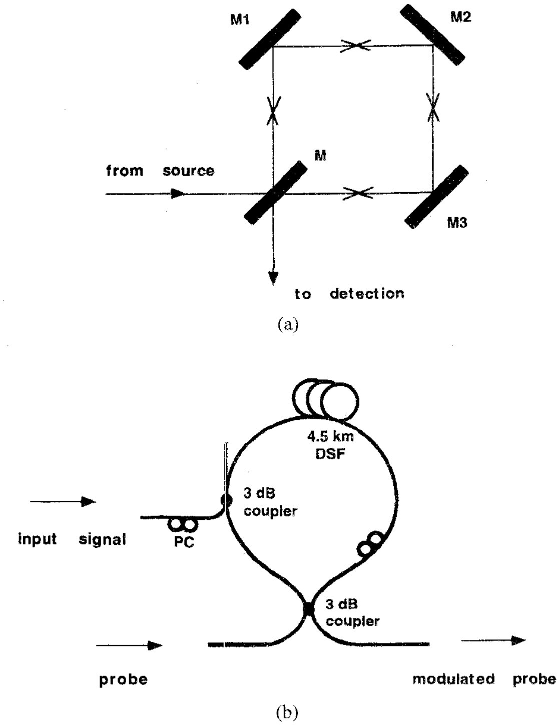


Fig. 6. (a) A classical Sagnac Interferometer consisting of a half silvered mirror M, and three full mirrors M_1, M_2 and M_3 and (b) a nonlinear optical loop mirror using a 4.5 km dispersion shifted fiber as a nonlinear optical element.

by the large chirp parameters in the cross-gain modulated wavelength converters discussed in the previous section. The cross-phase modulation effect is utilized in an interferometer configuration, typically in a Mach–Zehnder interferometer [39]–[41]. Fig. 5(a) shows an example of a Mach–Zehnder cross-phase modulation wavelength converter. Semiconductor optical amplifiers are incorporated in both arms and electrical currents are injected into both amplifiers. An input optical signal passes through one of the arms and modulates the phase of the arm. The interferometric nature of the device converts this phase modulation to an amplitude modulation in the probe signal. Similar interferometric conversion principles apply to a number of variations in waveguide configurations. The interferometer can operate in two different modes, a noninverting mode where an increase in input signal power causes an increase in probe power, and an inverting mode where an increase in input signal power causes a decrease in probe power. Compared to the cross-gain modulation method, the use of an interferometer greatly improves the quality of the converted signal in terms of chirp and extinction ratios. The signal-to-noise ratio is also affected by the spontaneous emission of the amplifier, but high power optical probe reduces the spontaneous noise background. This chirp reduction and the signal-to-noise improvement are more pronounced in a noninverting mode of operation [42]. Theoretically calculated relative intensity noise (RIN) is in the range between -140 and -120 dB/Hz, comparable with that of typical semiconductor laser diodes. In addition, the thresholding characteristics of the interferometer can increase the extinction ratio, and a negative power penalties can be obtained in the conversion when input signals of poor extinction ratios are used [39]. These thresholding characteristics, on the other hand, restrict the dynamic range of the input power and add extra difficulty in controlling input power levels. Fig. 5(b) and (c) shows experimental results from [43]. The figures indicate that a contrast ratio of 15 dB can be obtained for input optical power levels between -7 and -8 dBm, and bias currents between 39–42 mA. Hence, the input power level must be monitored and adjusted to better than 3 dB. Since the input power levels of WIXC are likely to be monitored and controlled accurately in any case, this power accuracy requirement may add negligible complexity to the system. The mechanism which limit the bit rate is identical to the case of cross-gain modulated semiconductor optical amplifier, and higher intensity probe beam allow the bit rate to extend to 10 Gb/s [44]. Relatively high quality of the converted signal make this approach extremely attractive.

3) Nonlinear-Optical-Loop Mirror: A nonlinear-optical-loop-mirror (NOLM) is essentially a Sagnac Interferometer implemented in optical fibers with a nonlinear optical medium. The basic operation principle of a NOLM resembles that of the classical Sagnac interferometer shown in Fig. 6(a). In 1925, Michelson and Gale used the Sagnac interferometer to detect rotation of the earth. A beam of light from a source S is divided into two beams by means of a half-silvered mirror M. The two beams are caused to traverse opposing paths around a loop formed by mirrors M_1, M_2, and M_3, as shown. The beams recombine at M and are reflected into an observing detector in which interference fringes are seen. In the absence of asymmetry in the two paths, i.e., no rotation, the fringes appear dark (destructive interference). As the rotation rate increases, the fringes will evolve bright and dark, alternately. Sagnac interferometers can be easily implemented by means of optical fibers and fiber couplers. Such fiber interferometers are widely used as high precision gyroscopes in aircrafts today. The NOLM is a fiber Sagnac interferometer with a nonlinear optical medium inserted in the loop. Fig. 6(b) is a nonlinear-optical-loop-mirror using an optical fiber as a nonlinear medium [45]. A probe beam is split into two by a 50:50 fiber coupler and propagates in both directions. In the absence of nonlinear interaction, the output port sees no probe beam. An input signal is coupled into the loop via a fiber coupler and propagates in a counter-clockwise direction. This signal modulates the optical index of the nonlinear optical fiber owing to an optical Kerr effect, and causes the phase of the probe beam propagating counter-clockwise to increase relative to that of the clockwise beam. Due to this asymmetry, the output port sees the probe beam. Due to a finite propagation time through the nonlinear element, the probe signal is pulsed (clocked) and needs synchronization with the input signal. All-fiber systems require more than 2 km of optical fibers, and unstable output can be caused due to local index variation in the fiber. Recently, a nonlinear optical loop mirror is implemented by insertion of a semiconductor optical amplifier as a nonlinear optical medium. The demonstrated system is far more compact compared to the all-fiber system. These semiconductor amplifier-based wavelength converters share characteristics discussed in Section III-B2), cross-phase-modulated semiconductor optical amplifier. Reference [46] discusses a polarization insensitive wavelength conversion in a NOLM at 10 Gb/s.

C. Wave-Mixing Wavelength Converters

Wave-mixing rises from a nonlinear optical res ponse of a medium when more than one wave is present. The outcome of wave-mixing effect is a generation of another wave whose intensity is proportional to the product of the interacting wave intensities. The phase and frequency of the generated wave is a linear combination of those of the interacting waves. Therefore the wave-mixing preserves both phase and amplitude information, and this is the only category of wavelength conversion that offers strict transparency. It is also the only method that allows simultaneous conversion of a set of multiple input wavelengths to another set of multiple output wavelengths. Last, this method can potentially accommodate signals with extremely high bit-rates exceeding 100 Gbit/s.

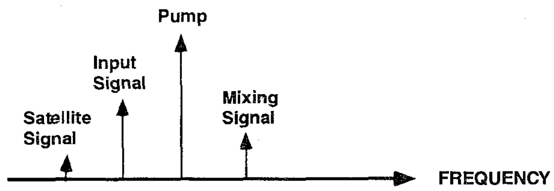
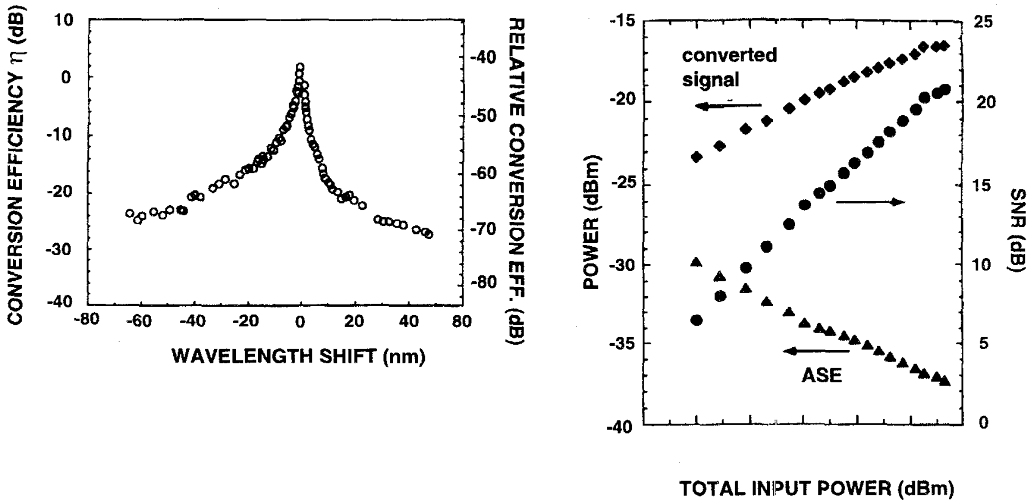


Fig. 7. A four-wave-mixing diagram shown in the frequency domain.

Depending on the number of interacting waves involved, they are called three-wave-mixing (two input waves and one output wave), four-wave-mixing (three input waves and one output wave), and so on. Four-wave-mixing is based on one order higher nonlinear optical effects (third order) as compared to three-wave-mixing (second order). Consequently, conversion efficiencies are in general much higher for the three-wave-mixing than for the four-wave-mixing. The wave-mixing effects considered for WDM applications are parametric, and the chirp is reversed during the conversion process. The parametric conversion process is classically free of excess noise unless an active material is used. Optical wave-mixing is typically far less efficient compared to microwave mixing unless high intensities are used. To enhance nonlinearities, a number of conversion techniques involve optical amplifiers, in which case the signal-to-noise ratio is degraded. Comparison of this category of wavelength converters with others should again take the black box approach considering both noise and conversion efficiency. The following two sections discuss four-wave-mixing and difference-frequency-generation in waveguides.

1) Four-Wave-Mixing in Passive Waveguides: Parametric four-wave-mixing in fibers or semiconductor waveguides has been utilized for wavelength conversion applications. A semi-classical picture of four-wave-mixing includes formation of a grating and scattering of a wave off of the grating. Two optical waves form a grating due to intensity patterns in the nonlinear medium. This can be a standing wave grating if the two waves have identical frequency and no relative phase jitters. The nonlinear material responds to this intensity grating by forming a refractive index grating (Kerr grating) or by forming a population grating. The latter occurs if the material changes its energy state due to optical intensity. If the two waves differ in frequency, the grating pattern sweeps in space at a rate corresponding to the frequency difference. If the material response is fast enough to follow this sweep, the grating efficiency is unchanged. However, if the grating sweeps at a faster rate compared to the material response, the grating efficiency will decrease. The third beam present in the



(a) (b)

Fig. 8. (a) The conversion efficiency as a function of detuning for four-wave-mixing wavelength conversion in a semiconductor amplifier (courtesy of [53]) and (b) the conversion efficiency, gain, and signal-to-noise ratio as a function of the power level for four-wave-mixing wavelength conversion in a semiconductor amplifier (courtesy of [53]).

material is scattered by the grating. This scattered wave is the wave generated as a result of a four-wave-mixing interaction of the three incident waves. The frequency of the generated wave is offset from that of the third wave by the frequency difference of the first two waves. If one of the three incident waves contain information (amplitude, phase, or frequency), and the others are constant, then the generated wave will contain the same information (except for a possibility of phase conjugation). It is worth noting that there is nothing that distinguishes amongst the three waves unless there is a selection rule imposed by the material and the polarizations. In other words, if two optical waves of two frequencies are present, there can be two possible combinations of four-wave-mixing, which produces two waves. Fig. 7 illustrates this example using a diagram in the frequency domain. Two input optical waves, a pump wave at ω_p and an input signal wave at ω_s are present in a nonlinear medium. The generated wave at $2\omega_p - \omega_s$ is a result of the pump wave scattered by a grating formed by the pump wave and the signal wave. There is another generated wave at $2\omega_s - \omega_p$, which is a result of the signal wave scattered by a grating formed by the pump and the signal waves. The intensity ratio of the first and the latter generated waves equals that of the pump and the signal waves. Typically this ratio is above 20 dB, and for this reason, the first will be called a converted wave and the latter a satellite wave. As the satellite signal wave and the pump wave can overlap in wavelength with another WDM channel, filtering has to be carefully executed to avoid crosstalk noise. System penalties beyond 3 dB can rise in high capacity WDM networks for a crosstalk level as low as -35 dB. Reference [47] discusses a relatively efficient method of reducing the pump signal and a amplifier background. By employing a four-wave-mixing medium within a fiber Sagnac interferometer, only the input and the converted signals are expected to appear on the input port. In practice, imperfection in the 50:50 splitter and birefringence along the fiber loop result in an incomplete nulling of the pump wave.

The conversion efficiency and the bandwidth of this process bear a strong relation to the waveguide dispersion and length. A longer interaction length allows more accumulation of generated wave, but the absorption and the dispersion may limit the useful length. In the case of semiconductor waveguides [48], the losses on the order of 2 dB/cm limits the useful device length to less than 1 cm. In this case, the waveguide dispersion is negligible, and the conversion bandwidth typically exceeds 20 nm. For optical fibers [49], losses are on the order of 0.3 dB/km, and fiber lengths exceeding 1 km are typically used. Dispersion, however, limits the product of the tuning range and the fiber length. Even for dispersion shifted fibers, a 3 dB reduction in conversion efficiency occurs at the product 10 nm $*$ 2 km. Typical conversion efficiencies are in the range of -20 dB for 17 dBm pump power for both semiconductor and fiber waveguides.

2) Four-Wave-Mixing in Semiconductor Optical Amplifiers: Four-wave-mixing in an active medium, such as semiconductor optical amplifiers [50] allows relatively efficient conversion owing to increased optical intensities and resonantly enhanced optical nonlinearities. In such gain enhanced four-wave-mixing, a population grating is formed unless special geometries are used [51], [52]. Population gratings are generally much stronger than phase gratings, and their scattering efficiencies decrease more steeply with detuning of the signal wavelength relative to the pump wavelength. In semiconductor amplifiers, at least three physical mechanisms form gratings. They are carrier density modulation, dynamic carrier heating, and spectral hole burning. These mechanisms have different lifetimes and scattering strengths, and the four-wave-mixing conversion includes contribution from all these effects. Fig. 8(a) shows the conversion efficiency as a function of detuning (courtesy of [53]). At a small detuning, a slow pop-

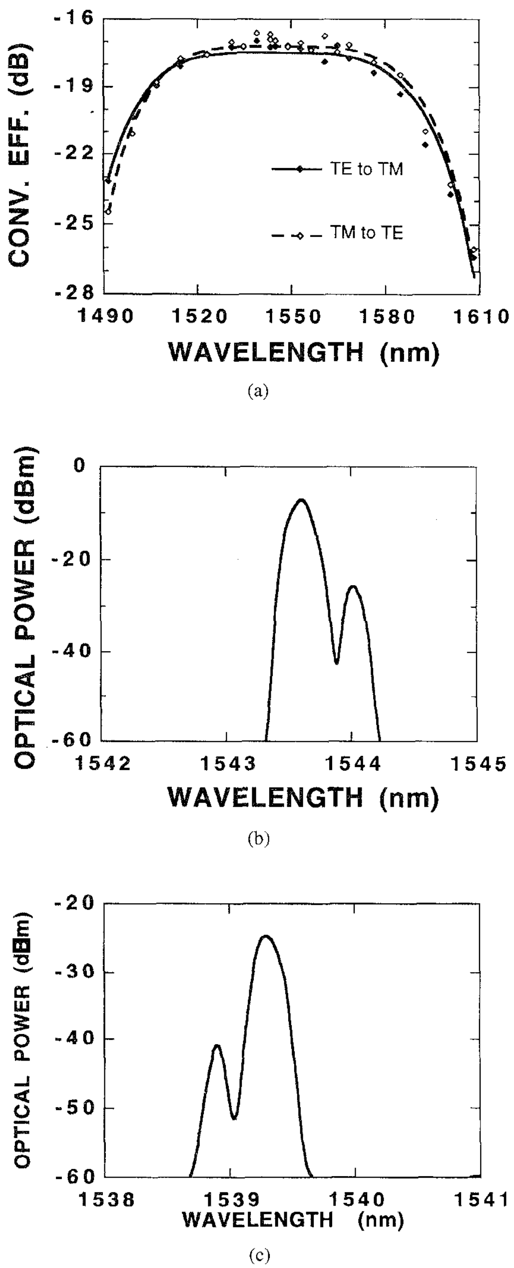


Fig. 9. Experimental results obtained in wavelength conversion by difference-frequency-generation. (a) Conversion efficiency curves for two input polarizations as a function of input wavelength. Also shown are the spectral inversion effects between, (b) the input wave spectrum, and (c) the output wave spectrum.

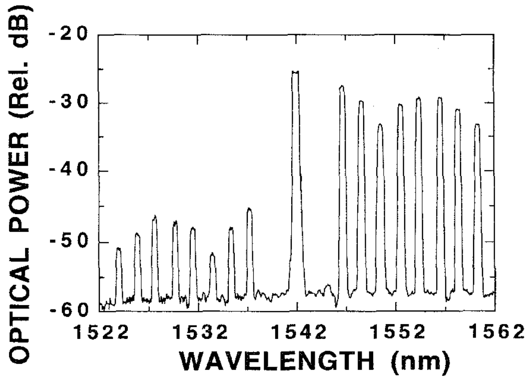


Fig. 10. Simultaneous conversion of eight input wavelengths (1546, 1548, 1550, 1552, 1554, 1556, 1558, 1560 nm) [59] to a set of eight output wavelengths (1538, 1536, 1534, 1532, 1530, 1528, 1526, 1524 nm) achieved by difference-frequency-generation. The structure at 1542 nm is a second-order diffraction of a pump wave at 771 nm.

ulation grating effect dominates, and shows a high conversion efficiency. At a large detuning, a fast phase grating dominates but the conversion efficiency is significantly lower than the peak value. The asymmetry in the spectra is a result of the asymmetric gain, interband-intraband dynamics, and coherence effects of various contributing mechanisms. Although the gain in the amplifier helps the conversion efficiency to approach 0 dB, it is difficult to achieve a 20 dB signal-to-noise ratio even with the use of a relatively narrow (0.08 nm) spectral filter. Fig. 8(b) shows the conversion efficiency, gain, and signal to noise ratio as a function of the power level.

3) Difference Frequency Generation: Difference-frequency-generation (DFG) is a consequence of nonlinear interaction of the material with two optical waves: a pump wave and a signal wave. DFG like four-wave-mixing in passive waveguides, offers a transparent wavelength conversion with quantum-noise limited operation. It is also capable of chirp-reversal and multiwavelength conversions. DFG wavelength converters based on a $LiNbO_3$ waveguide have been demonstrated [54], [55]. The normalized conversion efficiency is 41%/W-cm^2 which corresponds to a -6 dB conversion efficiency for a 2 cm waveguide and a 100 mW pump. Recently, DFG wavelength conversion in AlGaAs waveguides has been demonstrated [56], [58]. The main difficulty in realizing such a semiconductor wavelength converter lies in the phase-matching of interacting waves. Reference [57] discusses utilization of wafer-bonding and OMCVD growth to achieve periodic domain inversion for quasiphase-matching. Due to a large scattering loss in the waveguide the conversion efficiency was limited to -17 dB which is far below theoretically predicted -4 dB. Fig. 9(a) shows the conversion efficiency as a function of the input wavelength. The figure shows extremely wide conversion bandwidths exceeding 90 nm and polarization diversified operation. In the case of arbitrary polarization input, the conversion efficiency deviates by less than 0.4 dB from the value obtained with a TE or TM input polarization. This method also shows spectral inversion as in the case of four-wave-mixing. Fig. 9(b) and (c) show the measured spectra of the input and output waves. One key advantage of this conversion method is a capability to simultaneously convert multiple input wavelengths. Fig. 10 shows simultaneous conversion of eight input wavelengths (1546, 1548, 1550, 1552, 1554, 1556, 1558, 1560 nm) [59] to a set of eight output wavelengths (1538, 1536, 1534, 1532, 1530, 1528, 1526, 1524 nm). The structure at 1542 nm is a second order diffraction of a pump wave at 771 nm. Although four-wave-mixing can achieve similar multichannel conversion, DFG is free from satellite signals which appear in FWM (see Fig. 7). Difficulty in fabricating a low loss waveguide for high conversion efficiency is the main drawback of this method. On the other hand, strict transparency, the wide conversion bandwidth (90 nm), polarization diversity, polarization independent conversion efficiencies and spectrum inversion capabilities are some of the promising qualities of the semiconductor DFG conversion technique.

V. Conclusion

Wavelength conversion is a key function in providing full scalability in WDM networks. Wave-mixing converters are the only category of wavelength converters that offer a full range of transparency. Opto-electronic converters and optical gating converters offer limited digital transparency. The discussions are two-fold. What is the advantage of strictly transparent wavelength conversion over nontransparent wavelength conversion? Provided that we discard transparent wavelength conversion, what is the advantage of all-optical methods over O/E–E/O conversion? These discussions are similar to those on fiber-amplifiers versus optoelectronic repeaters. Fiber amplifiers are considered all-optical (no electrical signal routing) and strictly transparent. In reality, fiber amplifiers are rapidly replacing the optoelectronic regenerators that are already in place today. Deployment of fiber amplifiers in the trunk does not limit network users' access to signals of any specific protocols or formats. The upgrade of network capacity is simple in networks with such transparent elements. In addition, transparent networks can accommodate complex encrypting methods for enhancing the network security. The advantage of all-optical over optoelectronic methods becomes clear as multiple wavelengths are involved and as cost-effective management of crosstalk must be achieved. As WDM technology becomes viable, transparency becomes more important for seamless evolution of the network with full interoperability. Wavelength conversion methods with limited digital transparency are available today for deployment. On the other hand, wave-mixing wavelength conversion show its potential for strictly transparent WDM network applications.

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