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WAVELENGTH CONVERSION DEVICES AND TECHNIQUES

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Introduction

Wavelength division multiplexed (WDM) networks are currently subject to an immense interest because of the extra capacity and flexibility they provide together with the possibilities for graceful system upgrades. For full network flexibility it is very attractive to be able to translate the channel wavelengths in an easy way and preferably without opto-electronic conversion. Here, we will first briefly look at advantages of employing optical wavelength converters in WDM networks and next review the optical wavelength conversion devices with emphasis on recent developments.

Wavelength converters in WDM networks

Work on possible architectures for WDM networks with wavelength converters has just started with focus on capacity, failure recovery, scaleability and network complexity, e.g., [1-10]. Generally it is recognised that for a fully loaded network and a given number of wavelengths, the converters do not result in a significantly higher capacity. However, they make it possible to assign wavelengths on a link by link basis thereby relaxing the requirements to the wavelength precision throughout the network [3]. Moreover, wavelength conversion eases the recovery from link or node failures by allowing for local rather than global reconfigurations in the network.

Wavelength converters will be placed in the network nodes where they reduce the blocking of traffic. As seen in the examples of Fig. 1, they can be operated with either a fixed input wavelength and a variable output wavelength or a variable input and a fixed output wavelength. Only in a few cases will variable in- and output wavelengths be needed at the same time. A converter with a fixed output wavelength is simpler than one with a variable, but as seen in the examples of Fig. 1, the complexity of the wavelength converter is traded for that of the space switch. It can be added, that the space switching in Fig. 1 could be

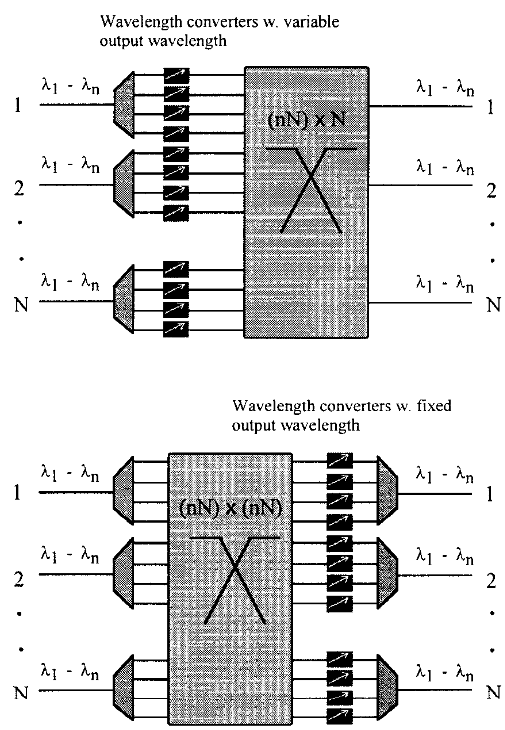

Fig. 1 Schematic of switch blocks with wavelength converters.

accomplished by employing one or two extra stages of wavelength converters [12].

For the switch blocks in Fig. 1 the enhancement in traffic performance due to the converters is illustrated in Fig. 2 that gives the blocking probability versus the traffic load. The benefits are most significant for small traffic loads whereas for high loads the performance is almost similar with and without converters. Because of the added equipment complexity due to the wavelength converters, the possibilities of sharing a bank of converters within a switch block [10] or only equipping part of the switch blocks within a network [2,7] have been considered.

A number of network and switch block experiments with wavelength conversion have been reported, e.g., [13-15]. Moreover, field trials for optical transport networks with wavelength conversion are planned. A fine example is the ACTS OPEN trial [16].

Wavelength converters are also important for the realisation of photonic packet switches, where they can be used to address free space in the optical fiber delay-line buffers [17-19] or to address output ports in the switch [19, 20]. Recent examples of packet switch block demonstrators with wavelength converters are reported in [21, 22].

Naturally, the converters must be transparent to the signal format (typically IM-NRZ). Bit rate capabilities of 10 Gbit/s will be sufficient for most systems considered today, and signal reshaping is in many cases desirable since other optical network elements can corrupt the signals. Multihop connections will be needed in most networks, so cascading of a few stages of converters must be possible. Moreover, the frequency chirp of the converted signals should allow for transmission over link lengths of typically 50-100 km. It is also important that the converters have a low electrical power consumption and operate at moderate optical power levels. In the following we review the progress in wavelength converters towards these goals.

Different types of wavelength converters

The wavelength converters can be categorised into four groups: 1) Opto-electronic converters, 2) laser converters, 3) coherent converters (four wave mixing

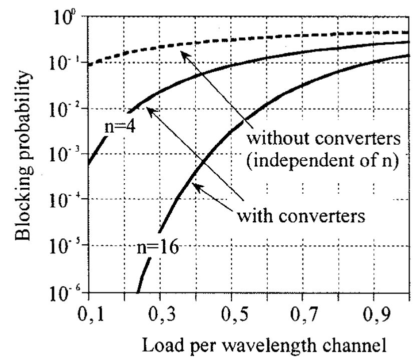

Fig. 2. Influence of wavelength conversion on blocking probability of a 16x16 WDM cross-connect (N=16) with the number of wavelength channels, n, as the parameter.

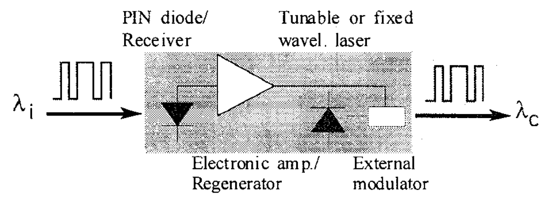

Fig. 3. Schematic of opto-electronic converter.

and difference frequency generation) and 4) converters based on optically controlled optical gates. The last three of these are all-optical type converters that avoid opto-electronic translation.

Opto-electronic converters

The straight forward solution to wavelength conversion is an opto-electronic unit consisting of a detector, an electronic amplifier or possibly a regenerator followed by a directly or externally modulated laser as shown in Fig. 3. This converter has low optical input power requirements, but it includes many components and has a high electrical power consumption, especially for high bit rates. A 4-channel 10 Gbit/s network experiment with opto-electronic converters in three nodes has recently been reported [13].

Laser converters

All-optical wavelength conversion can be performed very efficiently by optical control of single frequency lasers as shown in Fig. 4. The input signal (λ_i) to be converted is launched into the laser where it causes gain saturation that controls the oscillation of the laser.

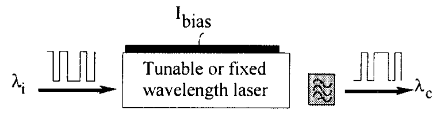

Fig. 4. Principle of wavelength converters based on semiconductor lasers.

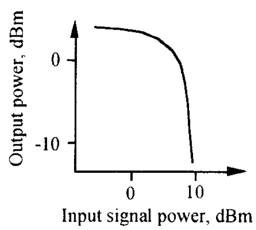

Fig. 5. Schematic of output versus input power characteristic for laser converter.

The result can be either IM or CPFSK output formats depending on the operation of the laser [23-25]. The lasing wavelength (λ_c) is either fixed or tuneable depending on the system requirements (cf. Fig. 1).

With steep input-output transfer functions (see Fig. 5) the IM output format mode can achieve fine signal waveforms that even allow for cascading of a few converter stages [26, 27]. The IM output mode is, however, associated with chirp [23, 28] that will limit transmission on non dispersion shifted optical fibers.

The problems related to chirp can be overcome by operating the laser well above threshold in the CPFSK output mode. In this case a frequency discriminator/filter is, however, needed at the output to obtain an IM signal format [23, 29].

Note, that the laser converter essentially consists of a single component, so it is very simple. Its optical input power requirements are 0-10 dBm and the maximum bit rate, determined by the laser's resonance frequency, is at least 10 Gbit/s [25].

Coherent converters

Converters that rely on four wave mixing (FWM) have been extensively investigated using both optical fibers [30] and semiconductor optical amplifiers (SOAs) as nonlinear elements (see references in [31]). FWM converters have many desirable features such as high speed operation, transparency to signal format

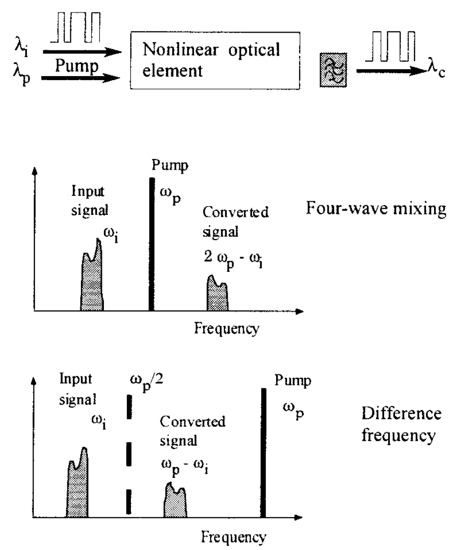

Fig. 6. Schematic of conversion in nonlinear element using four-wave mixing and difference frequency generation.

and the ability to convert several WDM channels simultaneously [32]. The conversion efficiency is, however, low (typically around -20 dB), so optical power levels of ~10 dBm have to be used for the pump of SOA converters while 10-20 dBm is needed for fiber based converters. Because of the low conversion efficiencies the signal-to-noise ratio for the converted signals needs attention, especially if converters have to be cascaded. Recent experiments using SOA converters with very long cavities have, however, resulted in conversion efficiencies approaching 0 dB [33] thereby making FWM more attractive. It should be noted, however, that the output wavelength is dependent on both the pump (λ_p) and the input signal (λ_i) wavelengths, so the pump must be tuneable even for converters with fixed output wavelength. Moreover, two pumps will be needed to ensure polarisation insensitive operation.

Wavelength conversion based on difference frequency generation (see Fig. 6) in periodically loaded waveguide structures of LiNbO3 [34] or AlGaAs [35] have also been reported. This conversion scheme features the same advantages and disadvantages as those of four wave mixing. The biggest disadvantage is the conversion efficiency that is presently around -27 dB. There are, however, prospects for improvement [35].

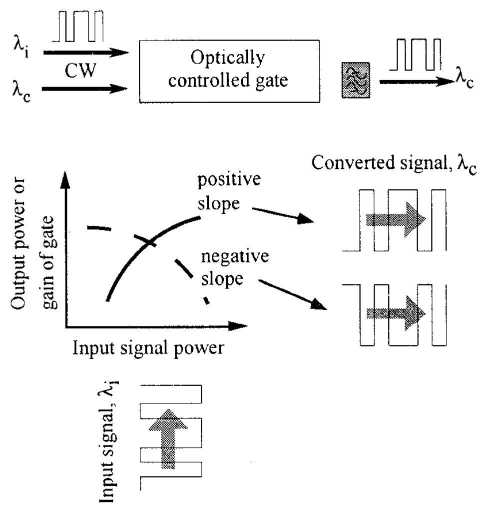

Fig. 7. Schematic of wavelength converter based on optically controlled gate and the dependency of the converted signal on the transfer characteristic of the gate.

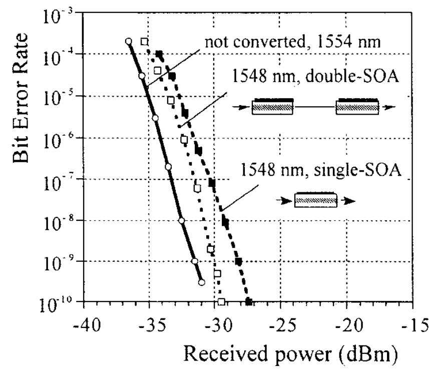

Fig. 8. Bit error rate for 40 Gbit/s signals: 1554 nm (input) and converted signals at 1548 nm using a single and double SOA converter [38].

Converters based on optically controlled gates

Converters made from optically controlled gates appear at the moment to be the most promising all-optical converter type. As illustrated in Fig. 7, the principle is to let the input power at λ_i control the gating of CW light at λ_c. Thereby the data are converted from λ_i to λ_c. The CW light originates from a light source with either a fixed or a tuneable output wavelength depending on the application of the converter (cf. Fig. 1). Clearly, the transfer function of the gate should be as steep as possible and depending on its positive or negative slope the converted signal will be in-phase or inverted relative to the input.

XGM gate

A simple optical gate is realised by a semiconductor optical amplifier (SOA) in which the gain saturation due to an optical input signal is used to control the gain and thereby the state of the gate [36]. The resulting converter, also called a cross gain modulated (XGM) converter, is extremely simple to assemble, polarisation insensitive and very power efficient. It has, however, a number of shortcomings: The signal is inverted relative to the input signal (negative slope) and the extinction ratio for the converted signal may degrade going from shorter to longer wavelength [37]. Moreover, the converted signal has a relatively large frequency chirp. Still, the converter has been used with acceptable results in a number of switch block experiments, e.g. [14, 20], and it remains attractive for many applications because of its simplicity.

The SOA-XGM converter can operate at surprisingly high bit rates. Recently we achieved 40 Gbit/s [38] using specially designed SOAs with the structure reported in [39]. As seen from Fig. 8, the penalties are only ~2 dB using two cascaded converters. A detailed analysis of the dynamics of SOA-XGM converters is found in [40]. It is shown that the gain saturation plays a significant role for obtaining the high bit rate. From the analysis it is also clear that a high conversion bit rate requires a high injection current to the SOA, a high confinement factor as well as high power optical input signals. Moreover, a high differential gain of the waveguide material is an advantage. Since the allowed injection current is limited the conversion speed can also be increased using longer cavity lengths. Cascading of two SOAs is an approach to a long cavity [41]. The amplifiers used in the experiments in Fig. 8 have lengths of 1.2 mm.

Obviously, the SOA converters add spontaneous emission noise to the converted signals. Still, with effective noise figures of 8-10 dB (including the input coupling losses of 2-4 dB), it is possible to cascade a few converters as shown in, e.g., [42].

XPM-gates

Converters based on optical gates that rely on changes in the refractive index due to optical input power have attracted a lot of interest. By placing the nonlinear element in an interferometer, the refractive index modulation can be used to intensity modulate CW light that is also launched into the interferometer. Therefore the converter is also named a cross phase modulated (XPM) converter. SOAs have been used as nonlinear elements in Mach-Zehnder (MZI) [43-45] and Michelson (MI) [46] interferometric structures as shown in Fig. 9. Nonlinear loop mirror configurations with either SOAs [47] or fiber [48] as the nonlinear elements have also been reported. It should be noted, however, that the nonlinear loop mirror configuration will only handle RZ signal formats.

The interferometric converters have the advantage of very steep transfer functions (see Fig. 9) enabling extinction ratio regeneration of the converted signal. As also seen, the conversion can take place on either the positive or the negative slope of the interferometer curve, where clearly the positive slope is the most attractive since the converted signal is non-inverted. Only small input signals are needed to introduce a π phase difference between the interferometer arms, so very efficient conversion is obtained. Because of the small modulation associated with the π phase shift, the frequency chirp of the output signal will also be small compared to, e.g., the XGM converter [46, 50, 51].

For stable operation the XPM converters must be monolithically integrated. During the last two years there has been a rapid progress in compact and efficient monolithically integrated converters [44-47, 52-55]. Several approaches are taken: Work on MZI-converters took its start in two-port devices [44, 45]. Next, more refined 3-port structures with an extra arm for asymmetric coupling of the input signal into one of the SOAs were developed [52-55]. The MI-converter is simpler since it offers direct access of the input signal to one of the SOAs [46]. Different approaches are also taken for integration of the SOAs into the interferometer: An all active approach, where both splitters and gain sections are made in the same material and where the gains in the different parts of the structure are determined by the bias current applied to the electrodes. This approach has the advantage of being simple and very compact [52]. The other approach is to have the active SOA sections coupled to passive waveguides leading to a simpler electrode structure and more well defined gain sections [53-55]. More work is still needed to determine whether the all-active or the active-passive approach should be taken.

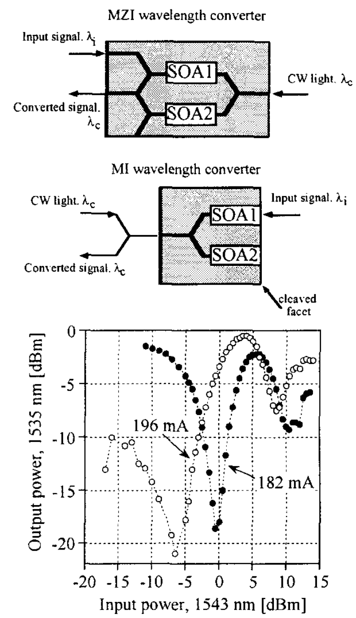

Fig. 9. Wavelength conversion principle using MZI and MI structures with SOAs. Examples of static characteristics of the MZI converter for two different bias currents to SOA2 are also shown [49].

Table 1. System penalty (in dB) for 5 Gbit/s conversion for different combinations of in- and output wavelengths using an all-active MZI converter. The power levels for input signal and CW light are 10 and 8 dBm.

Input wavelength, nm	Output wavelength, nm			
	1548	1552	1556	1560
1548	0	0.6	0.1	0.6
1552	0.2	0	0.1	0
1556	0.1	0.3	0.3	0
1560	0.4	0	0.2	0.6

As shown in the example of Table 1, the interferometric converters can work with low system penalties over a large wavelength range.

Besides signal waveform and spectral reshaping, the interferometric converters have fine noise properties because the noise is redistributed due to the transfer function (see Fig. 10) [56,57]. As a result, the noise is

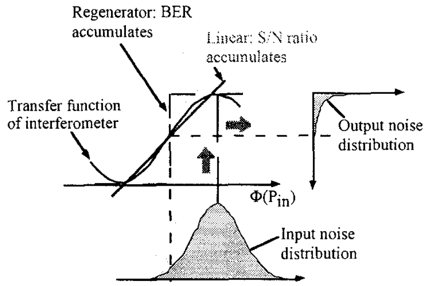

Fig. 10. Schematic of the reshaping of noise distribution in interferometric converter shown together with the transfer functions of the interferometer and those for an ideal regenerator and a linear element [57].

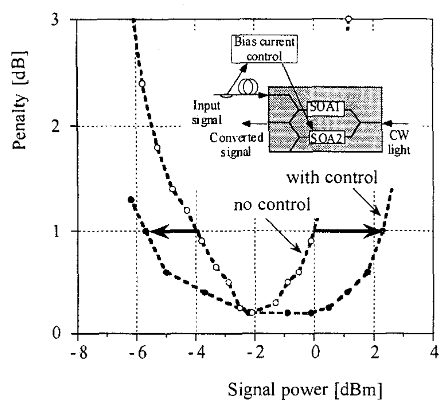

Fig. 11. System penalty versus optical input power with and without the use of the simple control set-up for compensation of variations in input power. The conversion experiment is performed with an active-passive MZI converter at 5 Gbit/s [49].

accumulating less rapidly than for a chain of optical amplifiers. This allows for cascading of several converters as has been shown in a transmission experiment with up to 10 cascaded converters [58].

The XPM converters with SOAs can achieve the same speed as the XGM-SOA converters provided that internal losses due to the integrated structure do not prevent high optical intensities in the SOA section. Several reports have been made on 10 Gbit/s conversion speed [46, 59, 60] and recently 20 Gbit/s conversion has been obtained with an all active Michelson structure [61].

The operating point of MZI and MI converters will be influenced by the optical input power level resulting in a small input power dynamic range. Clearly, some type of control will have to be established to maintain a stable operating point. Figure 11 shows an example of a very simple feedback loop used to control the bias of one of the SOAs in an active-passive MZI. As seen, the dynamic range is enhanced to 8 dB. For practical use passive phase control sections will possibly have to be added to the converters [61].

Conclusion

All-optical wavelength converters will be important for construction of switch blocks and flexible WDM networks. Many of the investigated converters have already shown impressive performances, but more research is needed to make the converters more user-friendly. New developments may for example include gates based on surface illuminated quantum well stacks [63].

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