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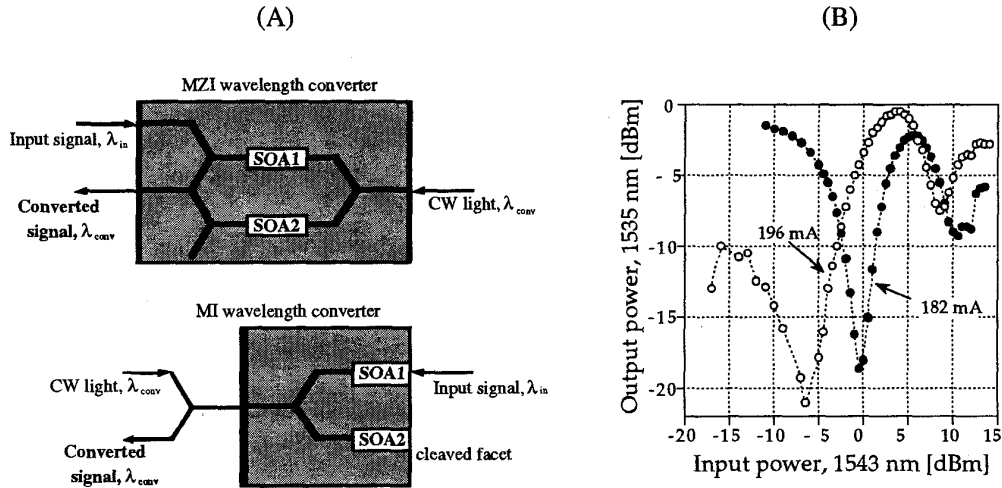
# All-Optical Wavelength-Shifting Technologies

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**Introduction:** Wavelength converters will enable construction of simple and flexible WDM networks, since they reduce the number of wavelengths needed and relaxes the requirements to the wavelength precision throughout the network [1]. In addition, wavelength converters can be exploited in space switches [2] as well as for TDM to WDM transmultiplexing [3]. Consequently, the development of effective and practical all-optical wavelength converters has attracted considerable attention. The most promising all-optical wavelength converters rely on optical modulation of gain or refractive index in semiconductor optical amplifiers (SOAs) [4]-[10] or lasers [11]. Especially, the optically induced refractive index change (cross phase modulation) in SOAs integrated in for example a Mach Zehnder, MZI, or a Michelson, MI, interferometer has recently resulted in very effective wavelength conversion. Desirable features such as effective up- and down conversion, high speed and polarisation independent operation as well as low chirping of the converted signals have been obtained [5]-[7]. Here, we outline the operation principle and performance of interferometric wavelength converters.



**Fig. 1:** (A) Wavelength conversion principle using MZI and MI structures with SOAs and (B) example of static characteristics of the MZI converter: Output power at  $\lambda_{conv} = 1535$  nm versus the input power at  $\lambda_{in} = 1543$  nm for two different SOA2 bias currents. Bias current to SOA1 = 300 mA. Input CW power = 6 dBm.

**Cross-phase modulation principle:** Wavelength conversion relying on cross-phase modulation in a SOA utilise that an increase in the optical input power will decrease the carrier density and in turn introduce a phase shift in the SOA. This principle is used in both the Mach-Zehnder, MZI, and Michelson, MI, interferometer (see Fig. 1.a). The MZI is formed by symmetric splitters and two SOAs such that the intensity modulated input signal is fed to only one of the SOAs. Therefore, the phase difference between the two interferometer arms will vary according to the digital information of the input signal. Wavelength conversion is obtained when CW-light with the desired output wavelength,  $\lambda_{conv}$ , experiences the modulation of the MZI transfer function. The MI converter that has a highly reflective facet (right facet in Fig. 1.a) works similar to the MZI. To accomplish high operation stability as well as small size, the interferometers and SOAs have been integrated [8]-[10].

**Performance of interferometric wavelength converters:** The static interferometer characteristic is shown in Fig. 1.b for a MZI with a separate input arm. The output power at 1535 nm (CW wavelength) versus the input power at 1543 nm (signal wavelength) verifies a pronounced interferometric behaviour: A change in input power of 10 dB leads to an output power change of 20 dB. Furthermore, by changing the bias current to SOA2 the MZI transfer function can be altered thus enabling adjustment of the conversion performance when the optical input power levels vary.

Bit-error-rate. BER, results for conversion of 10 Gbit/s data using the MI wavelength converter is shown in Fig. 2. The sensitivity is improved by 2 dB upon conversion due to an improvement of the extinction ratio from 7 to 11 dB (as discussed in Fig. 1.b). Furthermore, spectral cleaning is demonstrated by first transmitting the chirped 10 Gbit/s signal and afterwards transmitting the converted version of the same signal over 60 km of standard fiber. Clearly, the BER-curves show that the 4-5 dB dispersion penalty for the chirped signal is eliminated. This spectral cleaning capability of interferometric converters is very advantageous since it allows a chirped input signal (or even a multi-mode input signal) to be converted to an almost information bandwidth limited signal.

Similar excellent performance as described above can be obtained within a 30 nm wavelength range [7], [8], [9]. This is a unique property for the cross phase modulation technique in contrast to wavelength converters relying on for example cross-gain modulation [4] or four-wave-mixing [12] in SOAs. Furthermore, polarisation independent wavelength conversion has very recently been reported for a MZI converter [7].

Some of the excellent properties for the interferometric converter arise due to the operation principle where only  $\approx 4$  dB gain variation is required to change the phase in the SOA by  $\pi$  (shift from constructive to destructive interference or vice-versa). Therefore, the wavelength conversion is very power efficient. This can however, also be considered a disadvantage since the converter becomes very sensitive to input power variations that could occur in WDM networks. Figure 3 show that the 1-dB dynamic range is about 4 dB (open circles). However, as indicated in Fig. 1.b, control of the bias current to SOA2 provides a simple method for optimising the conversion performance of the MZI when the input power is changing. Current control can improve the dynamic range to 8 dB as seen in Fig. 3 (filled circles).

**Summary:** State-of-the-art results for interferometric wavelength converters have been presented. The interferometric converters are capable of high speed (10 Gbit/s), polarisation and wavelength independent (within 30 nm) wavelength conversion. In addition they offer unique features such as extinction ratio improvement and spectral cleaning. The 1-dB input power dynamic range is around 4 dB but can be increased to 8 dB by a simple control scheme.

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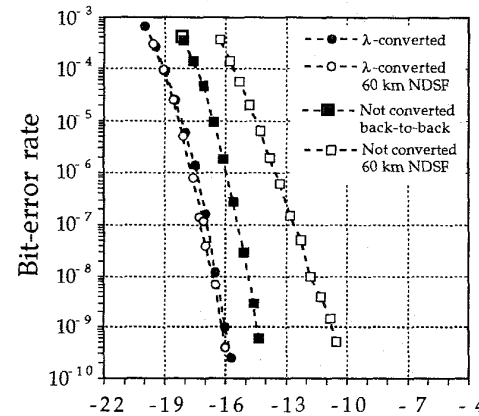


Fig. 2: Wavelength conversion of 10 Gbit/s data from 1556 to 1566 nm with extinction ratio improvement and spectral cleaning using a MI converter. Transmission is performed over 60 km of standard non-dispersion shifted fiber (NDSF).

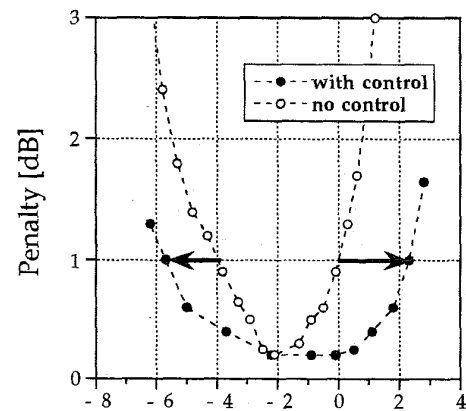


Fig. 3: Penalty at 5 Gbit/s for conversion from 1543 to 1535 nm versus average signal input power using a MZI wavelength converter. Curves are with and without adjustment of the bias current to SOA2.