Dispersion-induced Signal Distortion in Cascaded OADMs

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ABSTRACT

The optical add/drop multiplexer (OADM) is an important device in modern optical networks. Optical filters in OADMs often introduce group-velocity dispersion (GVD) and/or slope of GVD, the accumulation of which could distort the signals significantly. A computer model is built for commercial filters, accounting for the filtering gain and dispersion characteristics. When the model is incorporated into a network simulator, the filter dispersion is found to severely limit the number of OADMs that may be cascaded when transmitting 40Gb/s WDM signals with a channel spacing of 100GHz. As such high spectral efficiency difficult to achieve, the next considerations would be to transmit 40Gb/s over 200GHz channel spacing, or 10Gb/s over 50GHz channel spacing. The dispersion problem is mitigated, but still an un-negligible factor of limitation. For a large OADM network size, low-dispersion filters should be used, or a proper dispersion compensator is needed to offset the filter dispersion.

Keywords: signal distortion, dispersion, optical filter, OADM.

The optical add/drop multiplexer (OADM) has become an important functional element in modern optical communication networks, which greatly enhances the networking flexibility while reduces the equipment cost by eliminating the O/E/O signal converters. Furthermore, a network with OADMs supports all-optical paths that are transparent to both the signaling speed and the modulation format, hence is ready for future upgrade. Although the physical devices may vary, functional-wise an OADM always consists of an optical de-multiplexer (DEMUX), optical switches, and an optical multiplexer (MUX). Thin-film filters (TFFs) and fiber Bragg gratings (FBGs) are probably the most widely used optical filters for MUX/DEMUX in OADMs at present. The desirable filtering characteristics of such filters are wide, flat pass-bands and sharp transition edges to stop-bands at the same time. However, there is often a sizable group-delay dispersion associated to these filters, which could distort the signals badly, when the signaling speed is high and many filters are passed in series due to a cascade of OADMs. This paper investigates the limit of cascading OADMs imposed by the dispersion or dispersion slope of the optical filters. Both TFFs and FBGs have non-zero dispersion or dispersion slope, which distorts the optical signal. The distortion grows quickly when the signal has to pass through a number of optical filters. Previous work[1] has investigated the problem of filter dispersion slope and its impact on signal transmission through cascaded WDM filters. However, the study was for WDM NRZ-modulated signals at relatively low spectral efficiency. In this paper, TFF-based OADMs are used as examples to show how the filter dispersion slope seriously limits the cascade-ability of OADMs when the WDM system is operating at high spectral efficiency, as well as to demonstrate the effectiveness of a simple method of dispersion compensation using low-finesse Fabry-Perot (FP) etalons.

Fig.1 shows the intensity loss and the dispersion of a typical TFF used for 100GHz channel spacing. The dispersion is zero at the center frequency, but the dispersion slope is quite large. When the center frequency drifts due to manufacturing error or temperature fluctuation, the filter would manifest a nonzero dispersion at the signal center frequency. Tight manufacturing tolerance and temperature control could stablize the filter center frequency, or a tunable dispersion compensator may be used to offset the dispersion at the signal center frequency. The dispersion slope is however still there, which alone is a limiting factor. In one design of OADM, a channel has to pass such filter twice in the worst-case scenario. Also the channel has to be reflected by two similar filters that transmit the adjacent channels 100GHz away, one to the left and the other to the right. Fig.2 shows the reflective filtering characteristics to the signal under consideration, by the filter that transmits the channel to the left. The filtering characteristics by the filter to the right are similar, albeit the loss and dispersion curves are symmetric and anti-symmetric respectively to the ones in Fig.2 about the center frequency. It is noted that the dispersion or slope contributed by the reflective filters is in the same direction as the transmitting

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filter. The effects of transmitting and reflective filters are added up to distort the signal further. Things can get worse when thin-film-based wide-band filters are employed to MUX/DEMUX bands of WDM channels, and the channel under consideration falls at the transmitting/reflective edges of the band filters where the effect of dispersion is large. The dispersion characteristics of two band filters with 400GHz bandwidth are shown in Fig.3 for transmitting (left side) and reflecting (right side) a channel at the band edges. Once again, it should be noted that the band filter contributes dispersion/slope with the same sign as the channel filters do. The dispersion becomes insignificant for the two channels sitting around the center of the band filter.

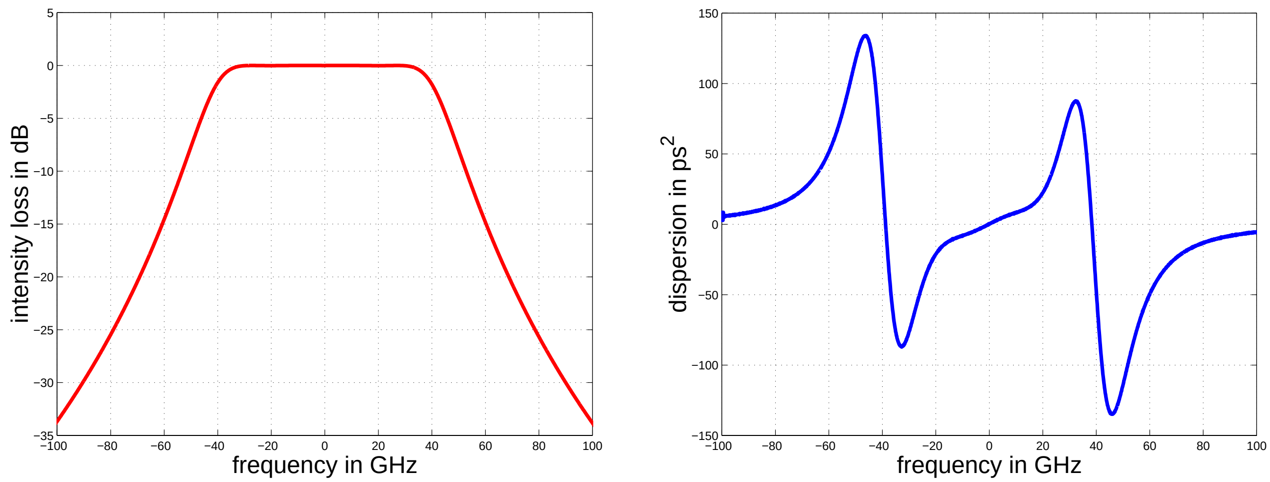

Figure 1. intensity loss and dispersion of a 100GHz optical filter in transmission.

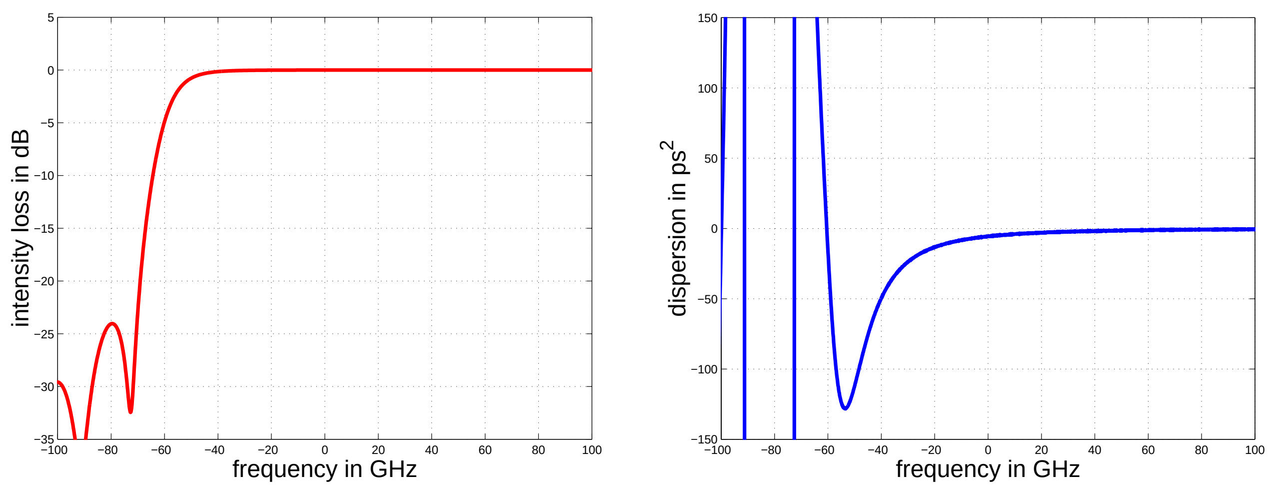

Figure 2. intensity loss and dispersion of a 100GHz optical filter in reflection.

We shall investigate 40Gb/s WDM systems with 100GHz channel spacing and the RZ modulation format. The RZ format is increasingly favored because of its robustness against fiber nonlinear effects. Using the VPItransmissionMaker$^{\mathrm{TM}}$, a 40Gb/s RZ WDM system is simulated, where the optical transmitters generate chirp-free RZ pulses with 33% duty-cycle as shown in Fig.4. The optical signals pass through a series of cascaded OADMs before reaching the receivers. In each OADM, an optical channel has to pass two channel filters in transmission, two channels filters in reflection, two band filters in transmission, and one band filter in reflection. Fig.5 and Fig.6 show the received signals after the 40Gb/s RZ pulses having passed one, two, or three OADMs

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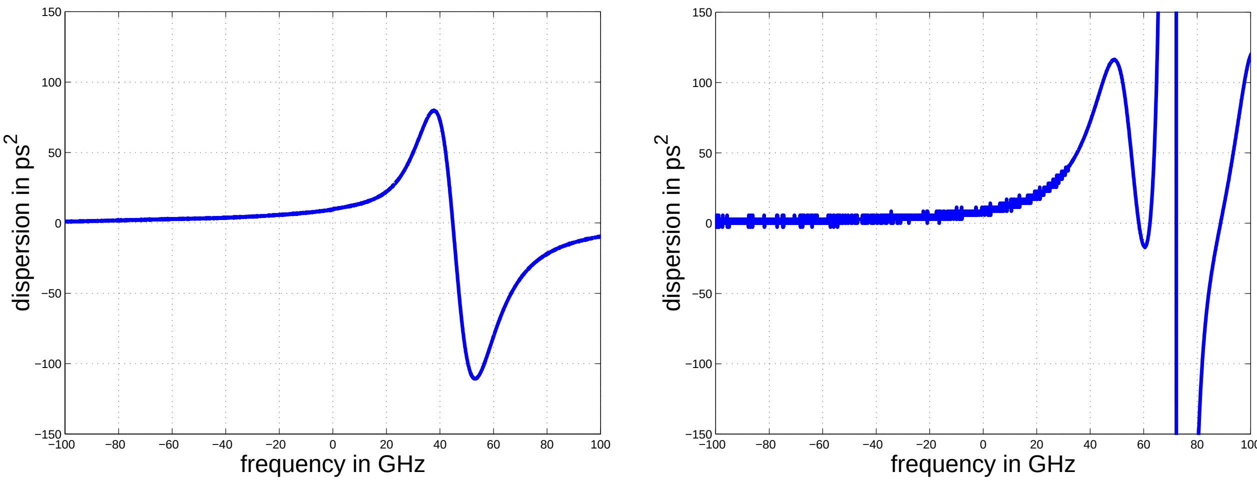

Figure 3. dispersion of 400GHz band filters. Left: the channel is at the "blue" edge of a band filter in transmission; Right: the channel is at the "red" edge of a band filter in reflection.

respectively. The optical filters cause large distortions to the signal. And the distortion is confirmed due to dispersion because it disappears completely when the filter phase is set constantly zero while the amplitude response is kept the same. The channels sitting at the edge of the band filters suffers significantly more distortion as a result of the dispersion effect of the band filters. The problem of dispersion is so serious that the 40Gb/s RZ signals can hardly pass two OADMs in cascade.

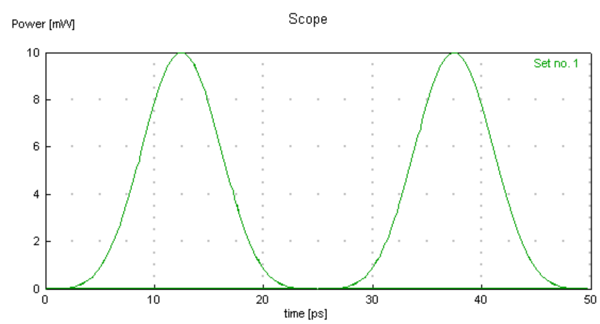

Figure 4. 40Gb/s chirp-free RZ optical pulses with 33% duty-cycle.

To overcome the severe limitation to the cascading of OADMs, specially designed optical filters may be employed to compensate the dispersion slope,[2] and particularly suitable are all-pass filters based on thin-film FP etalons.[3] We have designed a simple FP cavity to compensate the filter dispersion slope. The thin-film cavity is a low-loss optical filter whose response is periodic in frequency with 100GHz period, as shown in Fig.7. Within each period, the dispersion of the special filter is approximately opposite to that of the channel filters summed together. The compensating filter may be installed either before or after the OADM, and is capable of compensating the dispersion for multiple WDM channels. The effectiveness of such compensating filter is obviously seen from Fig.8 and Fig.9. Note that the compensating filter is optimized for the channels at the center of the sub-bands, which under-compensates the channels at the edges of the sub-bands. We expect that another similar compensating filter with a free-spectral range of 400GHz may be employed in conjunction with the 100GHz compensating filter, to have the edge channels better compensated. Alternatively, we may avoid using the edges of the band filters either by skipping channels, or by filtering the edge channels out using the corresponding channels filters in prior to the band filters.

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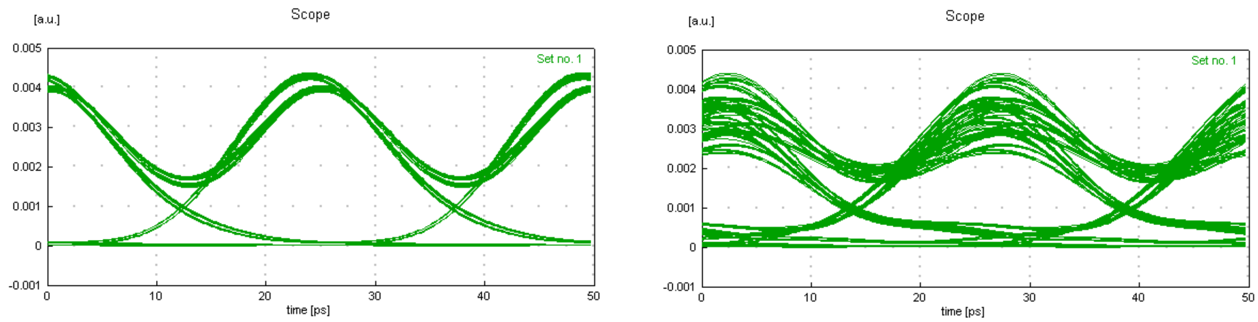

Figure 5. received 40Gb/s signals of a channel at the center of the sub-band after passing one (left) and three (right) OADMs, channel spacing 100GHz.

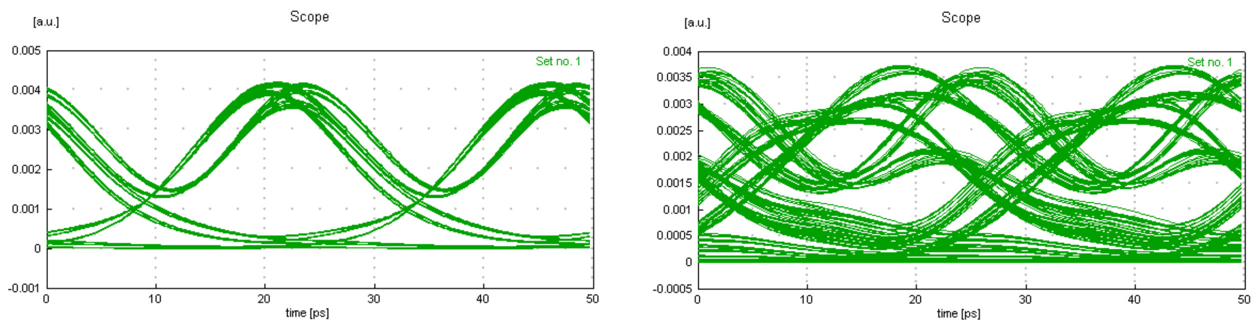

Figure 6. received 40Gb/s signals of a channel at the edge of the sub-band after passing one (left) and two (right) OADMs, channel spacing 100GHz.

In any case, the high spectral efficiency of 0.4 is rather challenging for long-haul transmission systems with many OADMs in cascade. The next, less-demanding goal would be a spectral efficiency of 0.2, which is realized in a 40Gb/s WDM system with 200GHz channel spacing, or a 10Gb/s system with 50Gb/s spacing. It would be interesting to see how much improvement is there and which system may perform better. Again 33% chirp-free RZ transmitters are used for both bit-rates. No band filter is assumed in the OADMs, because no such band filter is known available commercially for the channel spacing of 50 and 200GHz. Indeed, the cascade-ability of OADMs is increased significantly, as shown in Fig.10 and Fig.11, even without using any dispersion compensator. Somewhat surprisingly, the 40G-over-200G system performs better than the 10G-over-50G one. It seems that the dispersion (slope) of the optical filter scales up rather rapidly as the channel spacing decreases. With similarly designed FP compensating filters, drastic improvement has been achieved in the cascade-ability of OADMs, so much that the filter dispersion does no longer impose any detectable penalty to practical all-optically switched systems even with a large number of OADM nodes cascaded.

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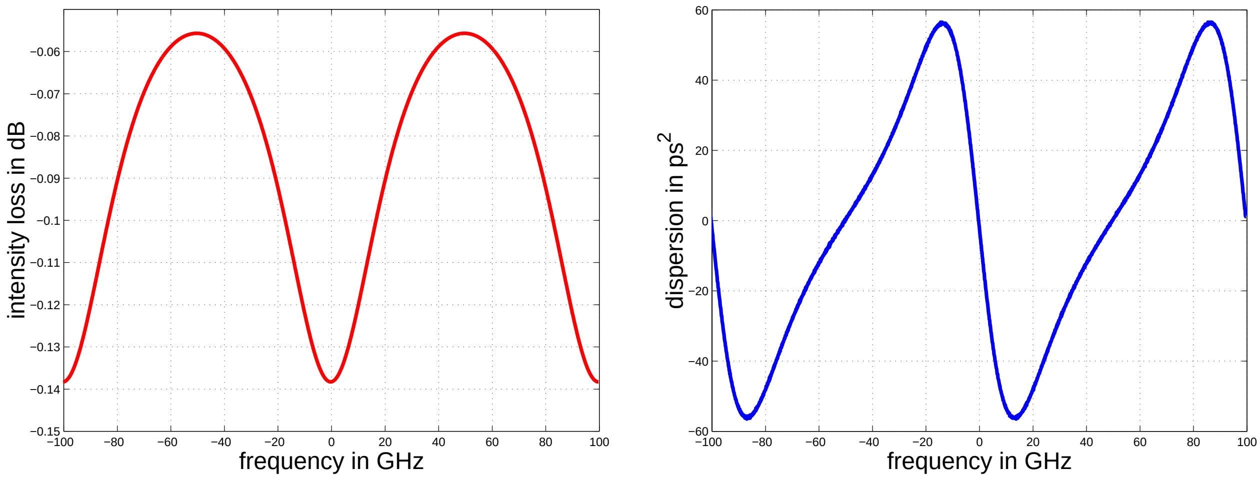

Figure 7. intensity loss and dispersion of an FP etalon.

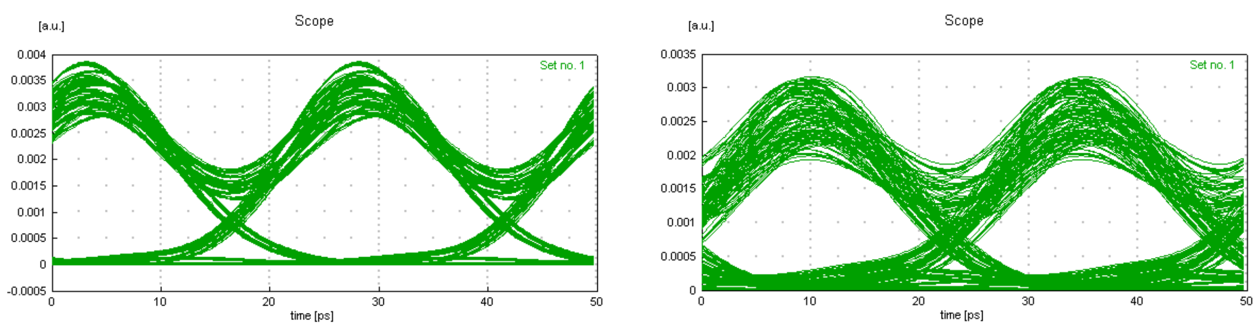

Figure 8. received 40Gb/s signals of a channel at the center of the sub-band after passing four (left) and eight (right) OADMs with dispersion compensation, channel spacing 100GHz.

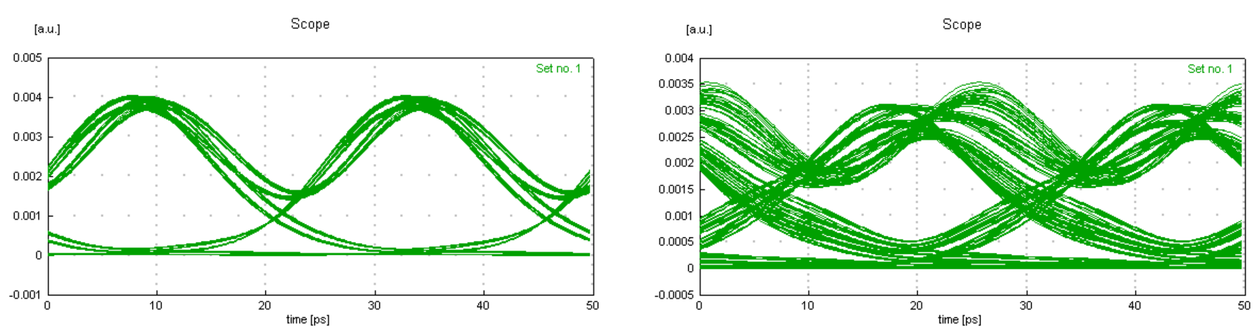

Figure 9. received 40Gb/s signals of a channel at the edge of the sub-band after passing one (left) and two (right) OADMs with dispersion compensation, channel spacing 100GHz.

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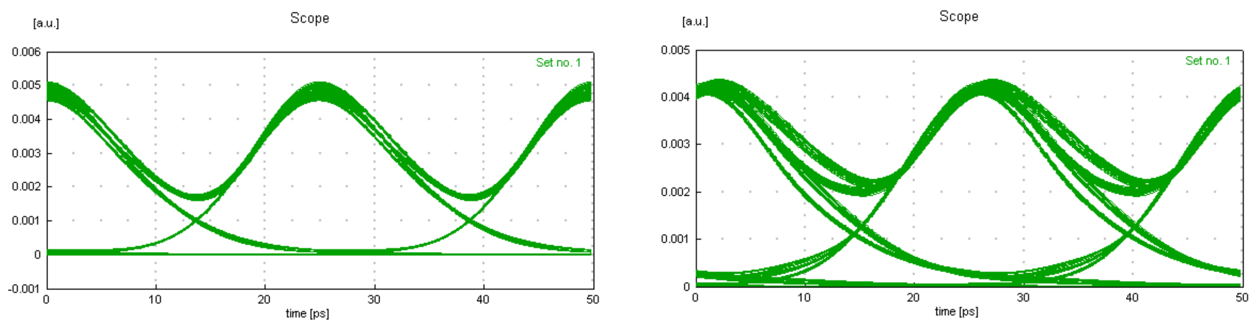

Figure 10. received 40Gb/s signals after passing four (left) and six (right) OADMs, channel spacing 200GHz, no band filter, no dispersion compensation.

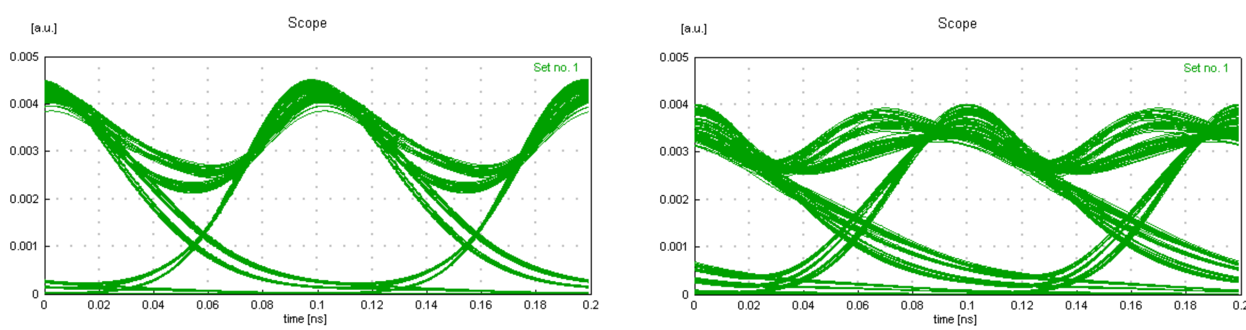

Figure 11. received 10Gb/s signals after passing four (left) and six (right) OADMs, channel spacing 100GHz, no band filter, no dispersion compensation.

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