Optical demultiplexer filtering to increase the uncompensated reach of 10-Gbit/s directly modulated lasers

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Significant uncompensated reach extension of highly chirped 10-Gbit/s directly modulated lasers is demonstrated by use of optical filtering provided by optical demultiplexers at the link end. Narrowband filtering narrows the optical spectrum of the chirped signal to minimize dispersion effects when the filter's center wavelength is appropriately adjusted relative to the laser wavelength. We show that an equivalent reach improvement is obtained with a dense wavelength division multiplexing (DWDM) demultiplexer as the filtering agent with optimal filter–laser alignment. Experimental uncompensated reach lengths of greater than 100 km of Corning LEAF® fiber are demonstrated, without the need for forward error correction. This represents a reach improvement of up to 50% in comparison with nominally unfiltered signal transmission. We also examine the correlation of performance with the filter insertion loss derivative. © 2005 Optical Society of America

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1. Introduction

While 10-Gbit/s directly modulated lasers (DMLs) are of interest for high-data-rate connections in metropolitan networks because of their potentially low cost and low power consumption, they also generally exhibit a high degree of transient chirp that severely limits their uncompensated reach lengths. The actual reach and dispersion tolerance of a given system is quite dependent on the particular chirp characteristics of the laser as well as the type of receiver used, e.g. preamplified or unamplified with PIN or avalanche photodiode (APD) detectors. One approach that has been demonstrated to increase the reach of these devices is transmission over a negative-dispersion fiber [1–4]. The interaction of the positive laser chirp with the negative fiber dispersion causes initial pulse compression and allows uncompensated transmission over 100 km, a distance suitable for practical metro networks. Another technique that has been applied with success to increase the reach length over standard single-mode fiber is narrowband filtering at either the laser or receiver ends of the link [5–7]. In one case a narrowband filter was used to narrow the spectrum and increase the extinction ratio of a DML with significant adiabatic chirp [5], and in other work the narrowband filter was applied in a sideband configuration to partially compensate for the effects of the laser chirp [6, 7]. These approaches demonstrated an increase in uncompensated reach by a factor of two or more over standard single-mode fiber. Other more recent work concerned with the problem of 10-Gbit/s DML transmission has focused on the use of electronic dispersion compensation (EDC) to extend the reach length, again over standard single-mode fiber [8–10]. At least some of these efforts also included the use of forward error correction (FEC) [9, 10].

In the work described here we concentrate on transmission of a 10-Gbit/s DML source over a nonzero-dispersion-shifted fiber with reach enhancement provided by optical filtering, without the use of EDC or FEC. The nonzero-dispersion-shifted fiber has positive dispersion at the transmission wavelength but with a lower dispersion value than standard single-mode fiber. We first demonstrate the level of reach extension possible with the application of a narrowband grating filter to a commercially available 10-Gbit/s DML device in a sideband filtering approach. The performance of the narrowband filter is compared with that of a wideband grating filter, and significant improvement is observed. We then extend these and the previously reported filtering related results to enhance 10-Gbit/s DML transmission by demonstrating that comparable reach improvements can be achieved by using common dense wavelength division multiplexing (DWDM) filters as opposed to special narrowband filters. Narrowband filters placed at either the transmitter or receiver end of the link are not necessarily practical solutions, since they add complexity to the system. However, a DWDM system already has filters as part of the system in the form of a multiplexer at the beginning of the link and a demultiplexer at the end of the link. We find that significant transmission performance improvement is made possible by simply placing one of these filters in an optimal wavelength alignment offset with respect to the 10-Gbit/s DML source laser wavelength. We also compare the total system performance for several different demux technologies, including a thin-film filter (TFF), an arrayed waveguide grating (AWG), and a fiber-based interleaver filter (ILF). The performance level is linked at least in part to the steepness of the filter transmission functions. We demonstrate the system transmission properties over a nonzero-dispersion-shifted fiber, Corning LEAF® optical fiber, and show practical transmission over distances of 100 km without the need for EDC or FEC, making the system suitable for most metro network link distances. The further application of EDC and FEC may allow uncompensated transmission over regional network distances. While the absolute distances achieved and shown here depend greatly on the dispersion value of the optical fiber, the significant new results of interest presented here are enhancements provided by different filters and the fact that common wideband optical demultiplexer filters can provide the same enhancement as a narrowband filter.

2. Experimental Configuration

The general experimental setup used for this study is shown in Fig. 1. A single-channel transmission system was employed to investigate the issue of fiber dispersion and its interaction with a chirped signal transmitted by a DML. The transmitter was a commercially available DML operating at 10 Gbit/s (NLK-1552-SSC). The laser was modulated with a pseudo-random bit sequence of length $2^{31}-1$ generated by a pattern generator. The nominal center wavelength of the laser was 1541.35 nm. The transmitter was operated with a laser current of 55 mA and a peak-to-peak drive voltage of 1.4 V. These parameters produced an extinction ratio of the 10-Gbit/s signal of ~ 8.0 dB.

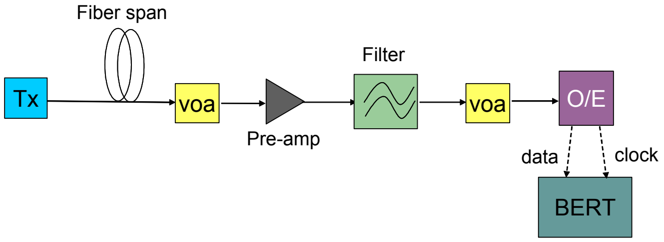


Fig. 1. Experimental test setup for 10-Gb/s DML filtering experiments.

As is seen in the figure, the DML signal was transmitted directly into the fiber span under test from the transmitter (Tx) with a launch power of approximately 2 dBm. A variable optical attenuator (VOA) controlled the signal power level into a preamplifier to keep the signal optical signal-to-noise ratio constant at a value greater than 35 dB among the different measurements and configurations. A stand-alone filter or demux filter followed the preamplifier, after which the signal passed through another variable optical attenuator to control the signal power entering the photodetector for optical-to-electrical (O/E) conversion. A bit error rate tester (BERT) was used to compute the signal Q values with the variable thresholding algorithm commonly used for Q estimation [11].

The fiber used in all the experimental tests was Corning LEAF optical fiber, an ITU standard G.655 compliant fiber. The dispersion value at the transmission test wavelength at 1541 nm was $\sim 3.5\,\text{ps}/\text{nm}/\text{km}$. This is a fiber widely deployed throughout the world, and its low absolute dispersion at 1550 nm offers a significant uncompensated reach advantage over standard single-mode fiber for many metro and regional network applications [12]. This fiber was chosen for the experiments to illustrate the practical reach lengths achievable with commercially available 10-Gbit/s DMLs over an nonzero-dispersion-shifted fiber that is already found in many networks.

The filters tested in the transmission system included two tunable-grating filters of bandwidths 0.22- and 0.6-nm. Then three different DWDM demultiplexer devices were also tested, such as might be found at the end of a WDM system link. These included an 8-channel 100-GHz TFF demux, a 40-channel 100-GHz AWG demux, and a 50/100-GHz interleaver filter.

2.A. Experimental Results

The first experiments conducted involved 0.22- and 0.6-nm tunable-grating filters. The 0.22-nm filter is a narrowband filter whose bandwidth is smaller than the bandwidth of the DML, and the 0.6-nm filter is effectively a wideband filter, significantly wider than the laser spectral bandwidth. Both filters have approximately Gaussian transmission functions, which are shown in Fig. 2.

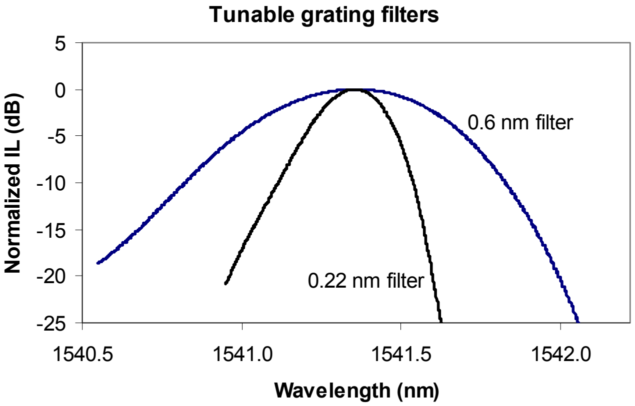


Fig. 2. Transmission functions of tunable-grating filters.

We first look at the Q performance of the system for transmission through 80 km of LEAF fiber. The laser wavelength was fixed at a nominal value of 1541.35 nm while each filter under test was tuned across the laser spectrum. The signal Q value was measured at each center wavelength position of the filter as it was scanned. The results for both grating filters are shown in Fig. 3. One aspect of the results that is immediately apparent is the asymmetry of the behavior with respect to the relative laser–filter frequency offset, an effect previously reported [6, 7]. For example, the narrowband filter's peak performance is for a relative laser offset of ∼ 7.5 GHz, whereas the performance for an offset of approximately −8 GHz is at a minimum. Similarly, the wideband filter's maximum *Q* performance is for a laser offset of approximately 20–25 GHz, but the performance is monotonically decreasing for negative offset values. These offset values represent the relative position of the laser peak wavelength with respect to the center wavelength of the filter. The observed asymmetry may suggest an adiabatic component to the laser chirp, as well as a greater chirp on the upward bit transitions (positive frequency excursions) than on the downward bit transitions (negative frequency excursions). The positive chirp would be preferentially attenuated by positive laser frequency offset as shown in Fig. 3.

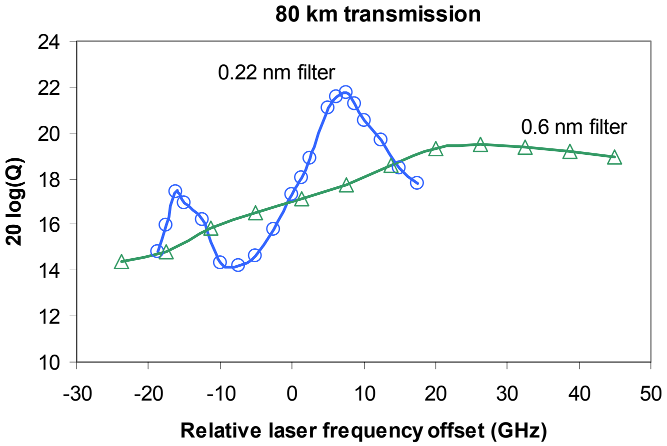


Fig. 3. Transmission performance over 80 km of LEAF fiber as a function of relative laser frequency offset from the center of the grating filter transmission function.

We also see from Fig. 3 that the narrowband filter provides transmission performance superior to the wideband filter when the maximum *Q* values are compared at the respective optimal filter positions. The 0.22-nm filter has a maximum *Q* value more than 2 dB greater than the maximum *Q* obtained with the 0.6-nm filter. However, the sensitivity of the performance to the exact position is also much greater for the narrowband filter. The primary difference between the two filters that may most greatly affect the transmission performance is the slope of the filter transmission at the bandpass edge, rather than the filter bandwidth [7]. We examine the correlation of the filter bandpass edge slope with performance in greater detail below. Examples of the signal spectrum before and after optimal filtering by the narrowband 0.22-nm grating filter are shown in Fig. 4. The optimal filtering with the narrowband filter significantly attenuates the spectral bump on the short-wavelength side of the spectrum (corresponding to the positive chirp component), and reduces the 20-dB bandwidth by approximately 25%. The smaller bump or shoulder on the long-wavelength side of the spectrum may represent the adiabatic chirp component wavelength of the signal zero bits. This is also slightly attenuated by the narrowband filter in the optimal offset position, which may slightly increase the signal extinction ratio.

The *Q* performance as a function of transmission distance over LEAF fiber is shown in Fig. 5 for the two grating filters. For each filter, the results are shown for the filter in a centered position (no frequency offset) and for the optimal laser frequency offset with respect to the filter center wavelength that maximizes the signal *Q* at a distance of 80 km over LEAF fiber. These results show that, with the laser optimally offset from the 0.22-nm filter wavelength by $\sim 7.5\,\text{GHz}$, transmission is possible through up to approximately 110 km of LEAF fiber with $Q > 18\,\text{dB}$. The 0.6-nm filter in its optimal position permits a distance of $\sim 90\,\text{km}$. The baseline case is the 0.6-nm filter with no frequency offset, since this configuration has little effect on the laser spectrum, which shows a transmission distance of $\sim 75\,\text{km}$. Compared with this baseline, the optimally offset narrowband filter produces an uncompensated reach extension of $\sim 35\,\text{km}$, or close to 50%. We also note that the signal power entering the optical preamplifier was kept constant at $-15\,\text{dBm}$ for all distances except at 105 km, for which the signal power was $-20\,\text{dBm}$ owing to the increased fiber attenuation loss. Thus the optical signal-to-noise ratio value of the 105-km measurement was slightly disadvantaged in comparison with the other distances for a given configuration.

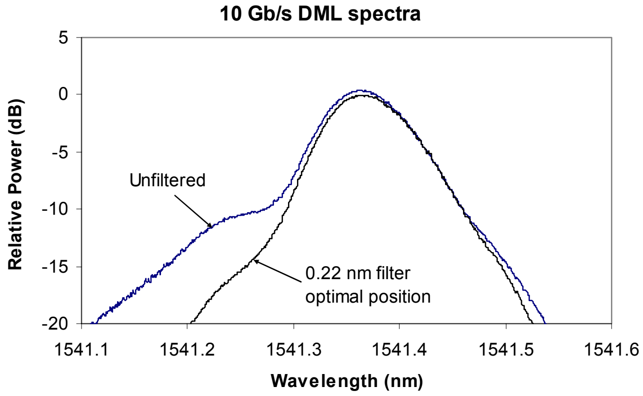


Fig. 4. Power spectrum of 10-Gb/s DML unfiltered and transmitted through the 0.22-nm narrowband filter in the optimal position to maximize signal quality at a distance of 80 km over LEAF fiber.

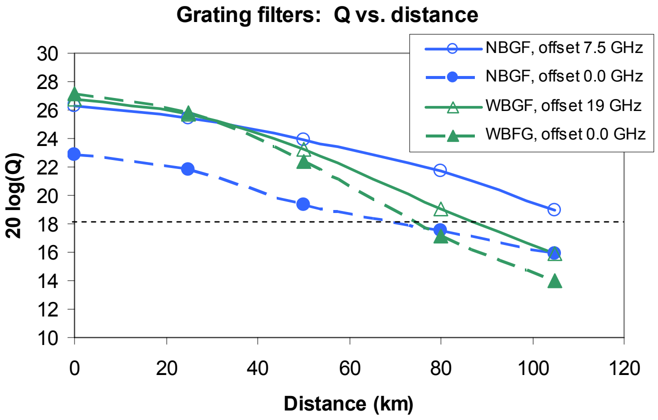


Fig. 5. Q as a function of transmission distance over LEAF fiber for narrowband grating filter (NBGF) with bandwidth 0.22-nm and wideband grating filter (WBGF) with bandwidth 0.6 nm.

In the preceding results we have seen how the appropriate application of a narrowband filter of 0.22-nm bandwidth in this case can significantly improve the uncompensated reach of a 10-Gbit/s DML. This is in agreement with results obtained previously with narrowband filters [5–7]. Although the experiments were conducted with the filter applied at the receiver end of the link, it could in principle be applied at any location, because dispersion is a linear effect. However, the introduction of a narrowband filter, which must be carefully aligned with the laser wavelength, may be impractical for application in real networks. It could add extra expense to the system, thus reducing some of the cost savings associated with the use of inexpensive DMLs. Therefore, it is of interest to investigate the performance of the 10-Gbit/s DML not through a narrowband grating filter but through conventional DWDM demultiplexers that would already be necessary components of a DWDM system in which the 10-Gbit/s DMLs were the channel transmitters. We now turn to experiments with DWDM demultiplexers used as the filtering elements to understand their relative performance to each other and to the narrowband grating filter previously studied.

The demux channel spacings investigated here were 100 and 50 GHz. The filter technologies studied were 100-GHz thin-film filters, 100-GHz arrayed waveguide gratings and 50/100-GHz interleaver filters. The basic experimental setup used to study these filters is the same as is shown in Fig. 1, except that the single tunable optical filter is replaced with the demux (or interleaver) filter under test. The 100-GHz TFF was part of an 8-channel demultiplexer, and the 100-GHz AWG was a 40-channel device. The 50/100-GHz ILF is a three-port device that separates a DWDM channel plan into odd and even channels in the two output ports. As shown in Fig. 1 and described above, a single channel with nominal wavelength at 1541.35 nm was input to all three devices during testing. However, as all three of these devices have fixed wavelength-filtering characteristics, the laser wavelength was tuned across the channel passband to determine the optimal relative alignment of laser and filter instead of tuning the filter as in the previous experiments with the tunable-grating filters.

The power transmission functions of the three demux filters are shown in Fig. 6 for the channel nominally located at 1541.35 nm. The 3-dB bandwidths of the 100-GHz TFF, 100-GHz AWG, and 50/100-GHz interleaver filters are 72, 64, and 43 GHz, respectively. Figure 6 also shows that the TFF and interleaver filter have transmission functions with steeper sidewalls than that of the AWG filter. The functions of these two filters are also somewhat flatter in the center than that of the AWG filter. We also note that the interleaver filter is centered approximately −0.05 nm away from the nominal channel wavelength of 1541.35 nm.

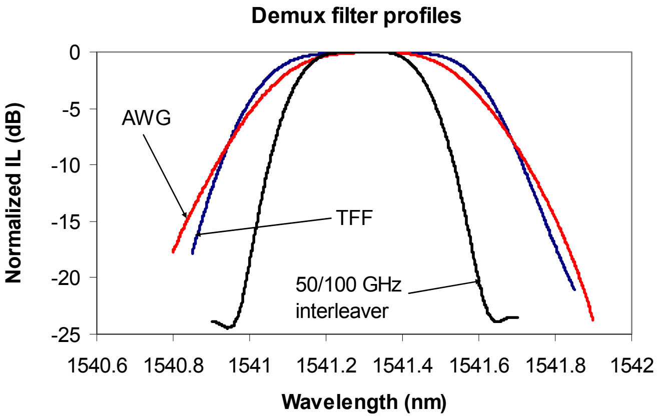


Fig. 6. Filter transmission functions for the 100-GHz TFF demux, 100-GHz AWG demux, and 50/100-GHz interleaver.

The results for experiments with the DWDM filters for transmission through 80 km of LEAF fiber are shown in Fig. 7. Also shown for comparison are the previously measured results from the 0.22- and 0.60-nm grating filters. Among other things, the results in Fig. 7 show that the 100-GHz TFF provides the same signal quality as the narrowband 0.22-nm grating filter when optimally offset from the laser center wavelength. This may seem a little surprising initially, since the TFF has a much wider bandwidth than the narrowband filter. However, we believe the TFF performs so well for a couple of reasons. One is that the TFF's steep sidewalls have a transmission slope comparable to the narrowband filter, and the TFF is thus able to significantly attenuate the high positive frequencies of the upward bit transitions while not affecting the rest of the signal spectrum. The second is that at the optimal position with respect to the signal spectrum, the filter's inherent negative-dispersion characteristic on the short-wavelength side [13], likely compensates for some of the fiber's positive dispersion. This partial dispersion compensation assists the spectral narrowing and reshaping to improve the signal quality over long transmission distances. Earlier simulations have shown that filters with different bandwidths but with the same edge slopes can have the same transmission performance when sideband filtering a 10-Gbit/s DML [7], and our experimental results are in at least qualitative agreement with those simulation results. The 50/100-GHz ILF achieves nearly the same level of *Q* performance (0.4-dB difference) as the TFF and narrowband filter. The best performance of the 100-GHz AWG is approximately 1.3 dB down from the TFF. The 0.6-nm grating filter has the lowest *Q* at its peak position. Moreover, all the filters show about the same signal quality with *Q* values of approximately 16.5–17 dB when the laser is not offset at all from the ITU grid frequency. The improvement from that value for their optimal laser–filter offsets is ~ 4.5 dB for the 100-GHz TFF and 0.22-nm narrowband filters for this 80-km transmission distance over LEAF fiber. The frequency ranges around the optimal values corresponding to a *Q* penalty of 1 dB or less are approximately 9 GHz for the TFF, 15 GHz for the AWG, 4 GHz for the ILF, and 6 GHz for the narrowband grating filter. Those of the TFF and AWG at least should be able to support the frequency-stability specifications for typical DWDM laser transmitters.

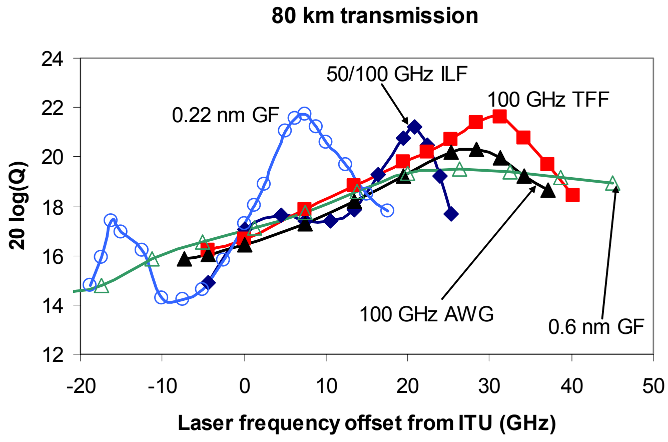


Fig. 7. Transmission performance over 80 km of LEAF fiber as a function of the laser frequency detuning for the 100-GHz TFF, 100-GHz AWG, 50/100-GHz ILF, and the 0.22-nm and 0.60-nm grating filters.

Bit error rate data as a function of received power in Fig. 8 shows that the TFF demux filter has a power penalty at a bit error rate of 1×10^{-10} of ~ 3.5 dB for transmission through 80 km of LEAF fiber compared with the back-to-back case, when the filter and laser wavelengths are optimally offset. However, there is clear evidence of an error floor in the case for which there is no filter offset and the laser is centered within the filter passband.

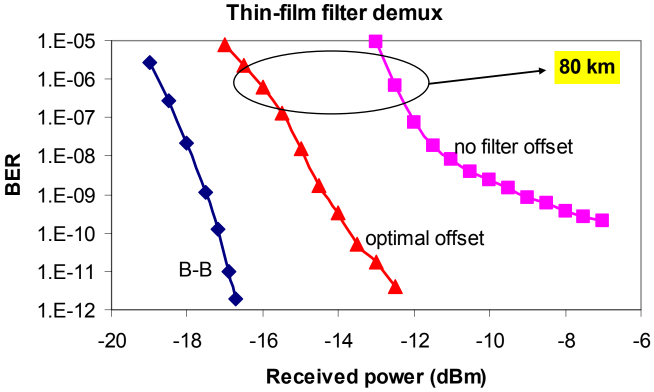


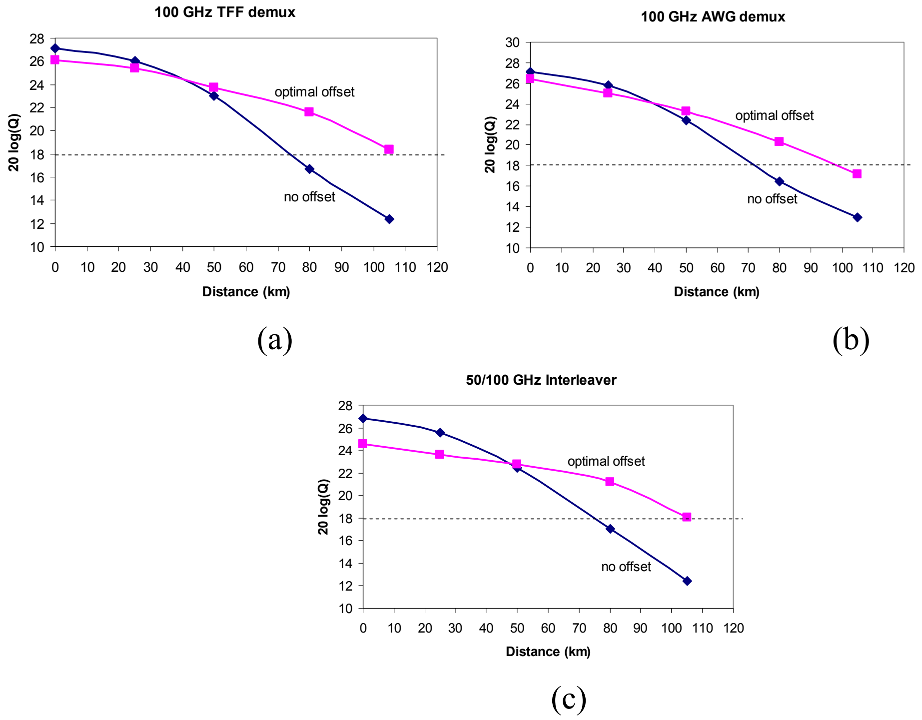
Fig. 8. Bit error rate waterfall data for transmission through 80 km of LEAF fiber and the 100-GHz TFF demux.

We next compare the performance of the various optical filters with the 10-Gbit/s DML as a function of transmission distance over LEAF fiber. Figure 9 shows the results for the TFF demux, AWG demux, and 50/100-GHz ILF, with data for both the optimal offset between laser and filter and for no offset. In each case the optimal laser–filter offset is defined as that determined for a transmission distance of 80 km. We see that for each of these filters there is a penalty for short transmission distances for the optimal filter offset, since it was optimized for the 80-km distance. This penalty arises from the distortion or eye closure of the filtered signal produced by the truncated spectrum. However, the filtered spectra produced by the optimally offset filters lead to significant signal quality enhancement over the longer transmission distances and produce uncompensated 40%–50% longer reach lengths (measured at $Q = 18$ dB) in comparison with the signals with no spectral modification when the laser and filters are aligned. This behavior is qualitatively similar to the comparison between uncompensated transmission of duobinary signals and conventional non-return-to-zero signals, in which the duobinary signal initially suffers a penalty for short distances but offers a significantly longer reach.

In Fig. 10 we show the results versus transmission distance for all five filters studied, with the performance maximized at 80 km by the appropriate laser–filter offset in each case. The results for the 0.22-nm narrowband grating filter and the 100-GHz TFF demux are nearly identical and produce the best overall results out to the maximum distance measured of 105 km. The 50/100-GHz ILF, while initially suffering a penalty relative to those filters for shorter distances, produces nearly the same Q values for 80 and 105 km distances and so offers essentially the same uncompensated reach length. The 100-GHz AWG demux Q data are slightly lower than the first three, with about a 1-dBQ disadvantage at 105 km. The 0.6-nm grating filter again has the lowest performance of the set.

2.B. *Correlation of Performance with Filter Steepness*

Given the relative performance of the five filters in improving the transmission performance of the 10-Gbit/s DML as seen in Figs. 7 and 10, we next examine that performance in terms of the filter transmission functions. As mentioned above, previous simulation and modeling results suggest that the primary filter characteristic influencing performance in this type of system is the filter slope at the bandpass edge [7]. We quantified this measure of the filter functions to see how well it correlates with the uncompensated transmission reach. The measure of filter steepness is the derivative, or slope, of the insertion loss function. We calculated the insertion loss derivative for each filter on one side (the shorter-wavelength side that provided the optimal filtering of the 10-Gbit/s DML signal) of the insertion loss function and plotted the derivative against the normalized insertion loss in Fig. 11. We see from the data that the three best performing filters have the highest insertion loss derivatives near the passband edges, where the normalized insertion loss varies from 0 to -3 or $-4\,\mathrm{dB}$. The lower performing filters (AWG and 0.6-nm GF) have smaller derivatives in this region. This supports the idea that the best performance is obtained when the unwanted higher signal spectral frequencies on one side can be effectively attenuated without significant effect on the lower spectral frequencies. In addition, it is likely that negative dispersion provided by filters such as the TFF also improve signal quality by partially compensating for positive fiber dispersion. The AWG filter tested is believed to have small absolute dispersion $(|D| < 5\,\mathrm{ps/nm})$ within its passband frequencies, and the performance of this device was likely primarily due to its insertion loss derivative. The dispersion characteristics of the interleaver filter were not available for this device. However, in general it is true that a filter's dispersion may play an important role in its performance for this application, with a negative dispersion at the appropriate filter edge able to enhance the reach further than that provided simply by the filtering alone.



(a) (b)

(c)

Fig. 9. Q as a function of transmission distance over LEAF fiber for (a) 100-GHz TFF demux, (b) 100-GHz AWG demux, and (c) 50/100-GHz ILF.

At least for this laser and the range of filter slopes exhibited by these filters, the optimal filter slope at the filter band edge (insertion loss IL ~ -3 to IL $\sim -4\,\mathrm{dB}$) seems to be approximately that of the TFF and narrowband grating filter. While the ILF performs nearly as well as those two, the data may suggest that filter slopes higher than that of the ILF might be somewhat less effective. However, we note that the dispersion value of the ILF at the optimal laser wavelength position is unknown, and this may also play a role in its relative performance.

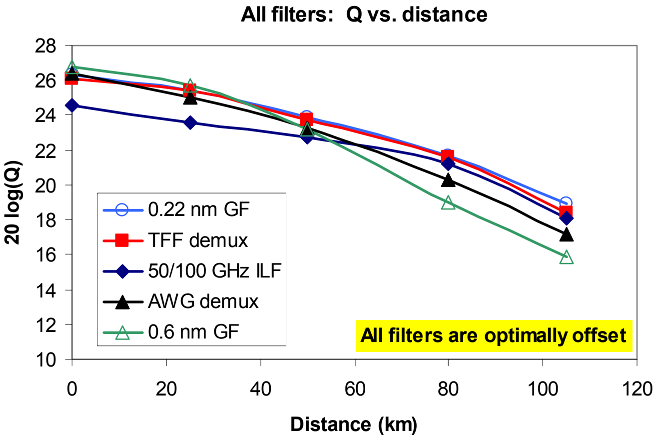


Fig. 10. *Q* as a function of transmission distance over LEAF fiber for all five filters studied with optimized laser–filter frequency offsets for 80 km.

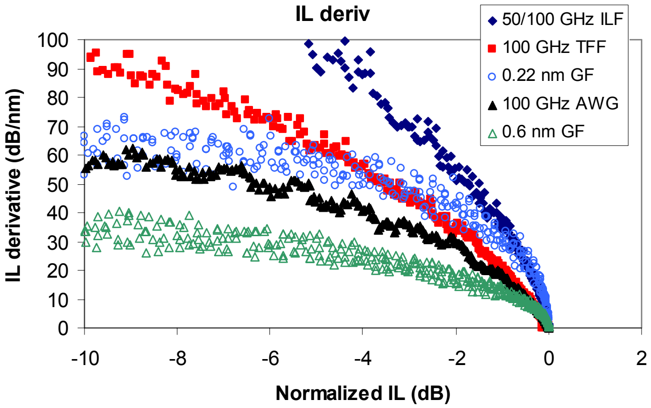


Fig. 11. Insertion loss derivative as a function of the normalized insertion loss for the five filters studied.

We note that our experimental configuration of Fig. 1 with only one filter before the receiver is slightly different from a DWDM system with a multiplexer at the transmitter end and a demultiplexer at the receiver end of a link. In a practical system, the mux and demux filters would likely be fixed in wavelength space, and the laser wavelength might be tuned to achieve the optimal laser–filter frequency offset to maximize performance. In that case the laser would be passing through two filters rather than one, but we believe that the relative performance of that configuration will be very similar to that of our experimental test setup. The effective filter slope of a cascade of two filters will be slightly higher than that of a single filter, but this may simply need a smaller laser offset from the nominal center frequency to achieve the optimal performance.

3. Summary

In this work we have experimentally demonstrated the reach extension of a 10-Gbit/s DML signal transmitted over a nonzero-dispersion-shifted fiber through filtering. We first showed that the application of a narrowband grating filter could increase the uncompensated reach over LEAF fiber by close to 50%, with a Q improvement of up to 5 dB at distances of $\sim$ 100 km in comparison with the baseline case of a wideband filter centered on the laser wavelength. We then demonstrated that performance equivalent to that for the narrowband filter could be obtained by use of only the demultiplexer filter that would already be part of a DWDM system. Three demux-type filters were studied, and we found that the 100-GHz thin-film filter demux performed equally as well as the narrowband filter. We found that filtering performance with the 10-Gbit/s DML is strongly influenced by the steepness of the filter sidewalls, as quantified by the filter insertion loss derivative. The filters improve the DML signal quality by preferentially attenuating the higher spectral frequencies on one side of the spectrum corresponding to the pulse leading edge chirp, as well as by inducing a negative dispersion in some cases that can partially offset the positive fiber dispersion. Thin-film filter technology appears especially well suited for this application because of the combination of steep filter sidewalls and negative dispersion at the low-wavelength edge of the bandpass region. The ability to use conventional mux–demux filters to perform the filtering operation may allow the transmission of these highly chirped lasers over practical distances of over 100 km of LEAF fiber without optical or electronic dispersion compensation.

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