Impact of cascaded thin-film filters on metro networks employing NRZ, LPF-DB, and CSRZ formats

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We studied the transmission performance of metro networks employing cascaded thin-film filters (TFFs) for three modulation formats including non-return-to-zero (NRZ), duobinary, and carrier-suppressed RZ (CSRZ). The effects caused by TFFs' dispersion and passband characteristics are investigated for 10- and 40-Gb/s signals, respectively. Simulation results show that the penalty resulted from dispersion can be partially compensated by the passband effects of the cascaded filters. CSRZ is shown to be a preferred format compared with NRZ and duobinary primarily originating from its good back-to-back performance.

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Thin-film filters (TFFs) have been widely employed in optical communication systems for their many attractive features, such as very low temperature dependence thus allowing operation without temperature controllers, flat-top passband to minimize the signal distortion, and relatively low insertion loss as well as little polarization dependency[1]. Also, modules based on TFFs can be designed to be upgradeable. The performance of cascaded TFFs in optical add/drop multiplexer (OADM) rings is of major importance in optical metro networks where the signals may go through a number of TFFs before being dropped at the destinations. However, the transmission characteristics of TFFs are different from other optical filters such as arrayed waveguide gratings (AWGs)[2]. Previous studies on cascaded filters' performance were mostly limited to power penalties for 10-Gb/s signals and only one modulation format[3−7]. In these studies, the dispersion was found to be the dominant factor of system penalty rather than the passband characteristics. Recently an investigation was carried out for non-return-to-zero (NRZ) and duobinary signals in a 10-Gb/s TFF based system, in which idealized model assuming a Butterworth filter shape and linear dispersion is used to describe TFFs[8]. To our knowledge no study has been carried out for TFFs with practical dispersion and passband characteristics, and the transmission performance of 40-Gb/s signals through TFFs has not been addressed.

Based on the measured TFF characteristics, we study the transmission performances of cascaded TFFs at 10 and 40 Gb/s. Three typical modulation formats with different properties are employed in our numerical simulation, which differ in pulse shape and phase information. They are NRZ, low-pass filter duobinary (LPF-DB) and carrier-suppressed RZ (CSRZ). NRZ is a simple and commonly used modulation format primarily due to its easy implementation. CSRZ has better spectral efficiency (0.8 bit/s/Hz) and is usually used in long-haul transmission systems. To further improve the dispersion tolerance, duobinary with narrow spectral width is proposed, however, its b-to-b performance is worse than NRZ and CSRZ[9]. System penalties caused by dispersion and passband limitations of TFFs are investigated in detail, and this would be helpful in designing metro networks built on TFFs. A simple analytical approximation is given to explain the combined impacts of dispersion and passband limitations on optical signals.

The impact of cascaded TFFs on 10- and 40-Gb/s signals is simulated for OADM networks using a model that includes a transmitter to generate NRZ, LPF-DB or CSRZ signals, a transmission link consisting of cascaded TFFs with the same central frequencies and an ideal photo detector. The TFF is described with the fitted data (Fig. 1(a)) from the measured transmission and dispersion of a TFF in an OADM module. The rise time is set to 1/4 bit period for NRZ signals. To generate 40- and 10-Gb/s LPF-DB signals, the 3-dB bandwidth of electrical filter is assumed to be 10.5 and 2.8 GHz, respectively. The duty cycle of the CSRZ signals is 67%. A pseudorandom bit sequence (PRBS) with a length of $2^{11}-1$ is used as the signal pattern. Their spectra and eye diagrams are shown in Figs. 1(b), (c) and (d), respectively. At the receiver, bandwidth limitation of the detector is not considered. As the electrical bandwidths of receiver components show significant impact on the electrical eye diagrams, here we only quantify the optical signal quality rather than the impact of the receiver. Eye closure penalty (ECP) relative to unfiltered NRZ signal is used to evaluate the signal quality under different situations. It is calculated by the following formula

$$C_{\mathrm{eye}} = -10\log(P_{\mathrm{R}}/2P_{\mathrm{av}}), \qquad (1)$$

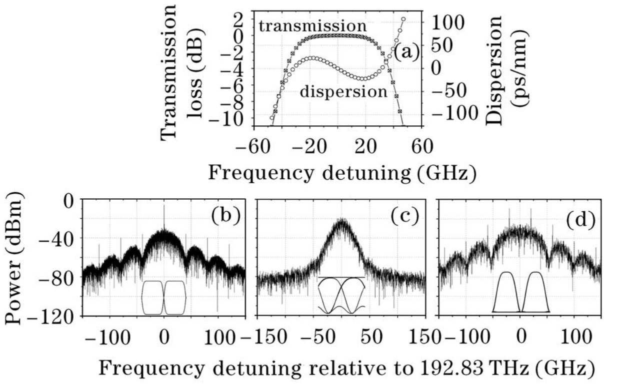

Fig. 1. Measured passband and dispersion characteristics of a TFF (a), and spectra and eye diagrams of NRZ (b), LPF-DB (c), CSRZ (d) signals.

where $P_{\rm av}$ is the average power of the received signal, $P_{\rm R}$ is the height of the rectangle window having a 20% bit-width that can be fitted inside the received eyes.

The simulation results at 10 and 40 Gb/s are shown in Figs. 2 and 3, respectively, where the number of 'loops' is the number of cascaded TFFs in transmission link. The b-b ECP of LPF-DB and CSRZ signals are 1.15 and −1.83 dB, respectively. The large b-b penalty of LPF-DB signal is due to the lower peak power and the narrow zero dip in its eyes caused by the residual light in '0' bits, and the CSRZ signal's negative b-b ECP owes to its higher peak power.

Since the dispersion and bandwidth narrowing are main reasons of the signal distortions caused by cascaded filters, both of these two factors are included in the simulation. Unlike the previous studies, the dispersion and passband effects of TFFs on system performance are investigated in a different view. The cases with only dispersion (Figs. 2(a) and 3(a)), and with only filtering effects (Figs. 2(b) and 3(b)) are simulated separately, then the combined effects of dispersion and passband shape are considered (Figs. 2(c) and 3(c)).

The simulation results for three modulation formats are compared firstly. Figure 2(a) shows that at 10 Gb/s, the dispersion induced ECP is correlated with the dispersion value, except for LPF-DB whose tolerance to dispersion is higher. While the effect of dispersion slope appears for 40-Gb/s signals because of their wider spectral width, the dispersion induced ECP (Fig. 3(a)) is not strictly related to the dispersion value. If the signals pass through filters without dispersion (Figs. 2(b) and 3(b)), it can be observed that, when the frequency detuning is increased, the ECP of the LPF-DB signal increases faster than that of NRZ or CSRZ signals. Namely, the format with wider spectral width is less sensitive to the detuning of the filter's central frequency, this can possibly be attributed to the vestigial sideband effects. When both dispersion and passband narrowing are considered, it is found that CSRZ at either data rate performs better than the others after transmission, as shown in Figs. 2(c) and 3(c). Contrary to the intuition, the excellent tolerance to dispersion of LPF-DB signals could not compensate its weak b-b performance, even after passing a number of filters (for example, 20 or 40). Only when the accumulated dispersion gets rather large (as in Fig. 2(c) at loop 70 and 10 GHz frequency detuning), LPF-DB can barely outperform NRZ.

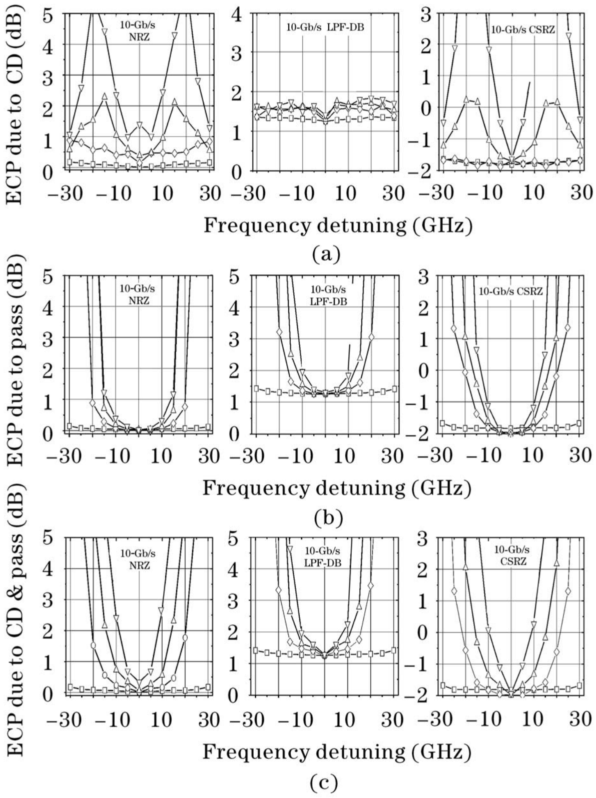

Fig. 2. ECPs caused by dispersion of cascaded TFFs (a), bandwidth narrowing of cascaded TFFs (b) and both dispersion and bandwidth narrowing of cascaded TFFs (c). Squares: loop 1; diamonds: loop 20; triangles: loop 40; inverse triangles: loop 70.

By comparing the penalties caused by dispersion (Figs. 2(a) and 3(a)) with that caused by passband effects (Figs. 2(b) and 3(b)), it is obvious that when frequency detuning is rather small like in most applications, the ECP introduced by the dispersion is larger than that caused by the passband effects. An interesting phenomenon we found is that, close to the central frequencies of TFFs, ECP due to the combined effects of the dispersion and bandwidth narrowing in TFFs is smaller than the sum of the penalties when dispersion and bandwidth narrowing are considered respectively. And in some cases, it is even smaller than that caused by dispersion only. To explain the observed phenomenon, a simple analytical model is derived for a stream of unchirped Gaussian pulses passing through a Gaussian filter with constant dispersion in its passband. After filtering, the electric field function of the n-th pulse in the stream is described by the following equation

$$E'_n(t) = A'_n \exp(i\omega_0 t)\exp(in\Delta\phi) \times \exp\left\{-\frac{(t-nT-t'_0)^2\tau_1^2}{2[\tau_1^4 + c^2D^2/(2\pi f_0^2)^2]}\left(1+i\frac{-cD}{2\pi f_0^2\tau_1^2}\right)\right\}, \quad (2)$$

in which T is the bit period, t'_0 and A'_n are time delay and amplitude of optical pulse after filtering, respectively, τ_1

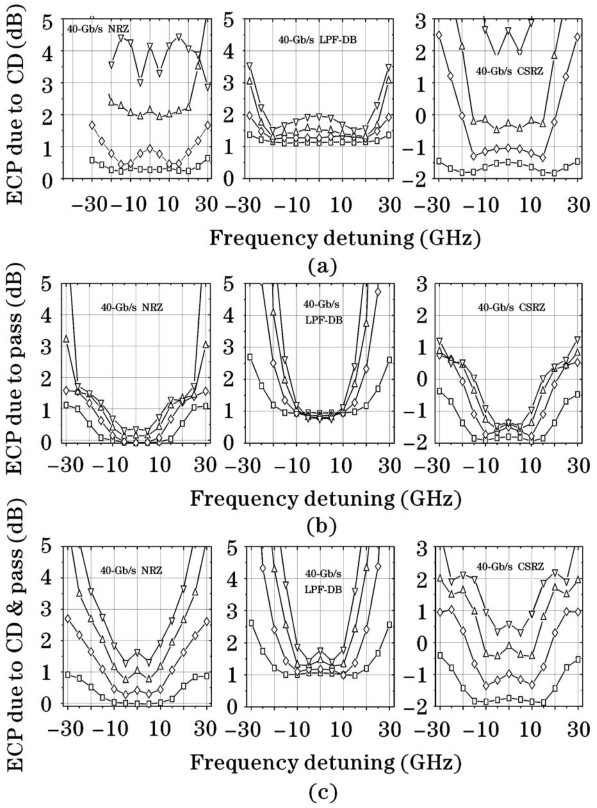

Fig. 3. ECPs caused by dispersion of cascaded TFFs (a), bandwidth narrowing of cascaded TFFs (b) and both dispersion and bandwidth narrowing of cascaded TFFs (c). Squares: loop 1; diamonds: loop 3; triangles: loop 5; inverse triangles: loop 7.

is a parameter that increases with the filter bandwidth narrowing, f_0 is the center frequency of TFFs, D is dispersion parameter, c is the light speed, and $\Delta\phi$ is a phase shift between neighboring optical pulses introduced by bandwidth limitation and frequency detune between the filter center and signal frequency.

According to Eq. (2), the pulse shape maintains to be Gaussian after filtering, and the pulse width is broadened by the dispersion and the passband limitation. We note that, τ_1 increases with the bandwidth narrowing, and, thus the dispersion-induced chirp $-cD/(2\pi f_0^2\tau_1^2)$ decreases, then the resulting signals will experience less penalty in the transmission through subsequent dispersive components. In addition, when the laser is detuned from TFF's central frequencies, the induced phase shift ($\Delta\phi$) between adjacent optical pulses will partially compensate the inter symbol interference (ISI) due to dispersion. This can be understood by considering three sequential bits like "1b1", the two "1" pulses would have different phases and the interference at the center of the middle pulse denoted as "b" would be partially destructed[10]. Therefore it can be explained that although the TFFs' passband limitation induces additional penalty by broadening the Gaussian pulse, it reduces the impact of filter's dispersion on the signals mean time.

It is also interesting to note that for 40-Gb/s signals passing through multiple TFFs, the optimal operating frequency is at a small detuning (~ + or −5 GHz), rather than at the filter's central frequency. It can be explained from above analytical derivation that, only when the signal's frequency is detuned from the filter center, the phase shifts between adjacent pulses will be introduced to partially reduce the ISI. This effect is absent for 10-Gb/s signals that are not sensitive to the dispersion slope potentially due to the relatively narrower spectral width. Therefore the optimal operating frequency of 10-Gb/s signals is at the zero dispersion frequency, namely the TFFs' center.

In this letter, we studied the system penalties due to dispersion and passband characteristics of cascaded TFFs based on the measured data of components. Extensive simulation is carried out for three modulation formats. The results show that, compared with NRZ and LPF-DB, CSRZ could offer not only the best b-b performance but also good transmission performance, unless the b-b performance of the other formats can be significantly improved. It is also pointed out that, certain improvement in transmission performance can be obtained for 40-Gb/s signals by slightly detuning the signal frequency with respect to the filter's center. A simple analytical analysis indicates that the ECP induced by dispersion in TFFs could be partially offset as the bandwidth limitation and frequency detune can not only reduce the chirp caused by dispersion, but also introduce a phase shift between neighboring pulses that can decrease the ISI.

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