Spectral filtering of multiple directly modulated channels for WDM access networks by using an FP etalon

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Spectral and waveform reshaping schemes can enhance the transmission distance of fiber links that use directly modulated lasers as transmitters. We prove the feasibility of using a simple Fabry–Perot (FP) etalon as the spectral reshaper for applications in wavelength division multiplexing (WDM) access networks. The transient chirp and adiabatic chirp of a directly modulated laser are analyzed in detail by using the time-resolved chirp measurement. The effects of the original extinction ratio and the adiabatic chirp on the spectral reshaping are clarified to obtain the optimal operation conditions. It is shown that placing a single-cavity FP etalon filter after multiple 10 Gbits/s directly modulated lasers can extend their transmission distances from <10 to >50 km in the 1.55 μm wavelength window. Due to the limited filtering capability of the etalon, the choice of the original extinction ratio and finesse of the etalon is discussed in detail from the experiments and simulation. © 2009 Optical Society of America

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1. Introduction

Directly modulated lasers (DMLs) are attractive for applications in metro and access networks. Direct modulation offers more compact and cost-effective solutions for optical transmitters compared to external modulation techniques using electro-optic modulators or electroabsorption modulators. It is well known that the major limitation for using DMLs in fiber links is the modulation-induced frequency chirp [1,2]. The transmitted optical pulses can be seriously broadened due to the interaction between the frequency chirp and the cumulative fiber dispersion along the transmission path. For example, at 10 Gbits/s, the span of a DML-based link is usually limited to around 10 km over a standard single-mode fiber (SMF) in the 1.55 μm wavelength band without dispersion compensation.

To enhance the transmission distance for a fiber link using a DML, many approaches have been proposed. Some approaches require changes in the fiber types [3,4] or replacement of deployed transmitters or receivers [5–8]. Some groups demonstrated spectral and/or waveform reshaping schemes for a DML to enhance the transmission distance [8–16]. The add-on component includes components, such as an optical filter [10,11], an optical delay interferometer (ODI) [15], and a birefringent fiber loop (BFL) [16]. The optical filter can, for example, be a fiber Bragg grating (FBG), an arrayed waveguide grating (AWG), or a thin-film filter. The multiplexer/demultiplexers (Mux/Demuxs) were also used to reduce chirping effects for wavelength-division-multiplexing (WDM) channels [12–14]. The drawback of using a Mux/Demux comes from the detuning of the laser wavelength to the slope of the filter response, which increases excess loss and signal fluctuation. The dispersion supported transmission (DST) scheme [8] and the chirp management laser (CML) [9] are other attractive schemes to extend the link span of a DML over hundreds of kilometers without dispersion compensation. The former scheme combines frequency-shift-keying- (FSK-) like modulation and a special detection scheme. The latter utilizes an optical spectral reshaper (OSR) and a special chirp condition, where the adiabatic chirp of the CML is set to half of the bit rate to have a π phase shift during each space bit. The OSR is used as a narrowband optical filter to increase the extinction ratio

(ER) as well as to change the chirp characteristic. These schemes are very attractive for metro applications. However, they require either a special receiver circuit or an accurate control of the operation condition.

This paper aims to develop cost-effective directly modulated transmitters for access network applications. The spectral reshaping scheme is adopted, but the requirement on the filter response is relaxed. In the previous schemes, a narrowband filter, such as a multicavity etalon or fiber grating, is used to provide the required steep spectral slope for reshaping. This requires a tight wavelength control to align the lasing spectrum to the edge of the filter response, which in turn makes the schemes sensitive to fluctuations on ambient conditions and difficult for multichannel reshaping. These schemes may also be subject to a larger insertion loss, which can be critical for access networks where the optical power budget is tight. In this paper, a Fabry-Perot (FP) etalon with low finesse is placed after the DML to reshape the spectrum and waveform of the DML output.

The FP etalon is a popular choice to monitor the wavelength of optical transmitters [17]; therefore its thickness can be accurately fabricated to match its frequency position and free spectral range (FSR) to the DWDM channels. The FSR is defined as the resonant mode spacing of the etalon, which can be expressed as $\mathrm{FSR}=c/2n_gL$ with L being the cavity length and n_g being the refractive index of the cavity. The symbol c represents the speed of light.

The proposed scheme can simply compensate multiple DWDM lasers with a piece of glass. A FP etalon can be very compact and low cost. It can also be easily packaged with a DML. In this paper, we first investigate the chirp characteristics of DMLs by using the time-resolved chirp (TRC) measurement [18]. We then demonstrate experimentally the feasibility of using a single-cavity FP etalon to compensate multiple 10-Gbits/s DMLS. Finally, a power-penalty simulation indicates what the optimal conditions are for the original ER of the DML and the 3 dB bandwidth of the etalon.

2. Operation Principles

2.A. ER and Chirp

In a DML, the chirp is mainly caused by the change in the refractive index for the carrier modulation as well as the power-dependent photon intensity distribution along the laser cavity [19]. The chirp of a single-frequency laser can be described by the following equation [20]:

$$\Delta v(t) = \frac{\alpha}{4\pi}\left\{\frac{\mathrm{d}}{\mathrm{d}t}[\ln(P_L(t))] + \kappa P_L(t)\right\}, \tag{1}$$

where $P_L(t)$ is the laser power. The parameters α and κ are the linewidth enhancement factor and adiabatic chirp coefficient, respectively. The α-parameter describes the relationship between how the real and imaginary parts of refractive indices are affected by the carrier density. The first term of Eq. (1) represents the transient chirp, while the second term is the adiabatic chirp. The adiabatic chirp can be distinguished from the transient chirp since the adiabatic chirp appears as a frequency offset between the mark (1) and space (0) signal levels. On the other hand, the transient chirp appears on the signal level as the light intensity is changing with time. The adiabatic chirp coefficient, κ, is the proportionality factor that relates the adiabatic chirp to the laser power change.

The transient chirp is determined by the changing rate of the output power during the transition of signal levels. If the rise time and fall time of the signal transitions are fixed, the transient chirp increases with the ER. The ER is determined by the bias current I_b and modulation current I_m as

$$\mathrm{ER} = \frac{1 + I_m/I_b}{1 - I_{th}/I_b}, \tag{2}$$

where I_{th} is the threshold current.

The adiabatic chirp is a key parameter for spectral reshaping and can be rewritten as

$$\delta v_a = \frac{\alpha \kappa}{4\pi} \rho I_m, \tag{3}$$

where ρ is the slope efficiency of the laser and is defined as the differentiation of the laser output power with respect to the injected current. From Eqs. (2) and (3), the adiabatic chirp increases with ER by varying the modulation current while fixing the bias current. On the other hand, it remains nearly constant if the modulation current is fixed and the ER is adjusted by varying the bias current. For a typical DML, the ratio of adiabatic chirp to modulation current is around a few hundred megahertz per milliampere [21]. Thus, the adiabatic chirp is of the order of 10 GHz for tens of milliamperes of modulation current.

If chirping is the major limiting factor for signal transmission using DMLs, low ER modulation should be used. However, the signal quality will suffer from the low ER penalty at the receiver end. This can be overcome by using a spectral filtering scheme after the DML in order to enhance the ER without raising the signal chirp.

2.B. Optical Filtering

To expand on the principle of spectral reshaping for DML signals addressed in the literature (e.g., [12,14]), a simplified model will be used here to clarify the filtering effects. The transient chirp is first neglected. Under the approximation that the signal transition and the phase continuity are neglected, the output signal $P_a(t)$ of a DML [Fig. 1(a)] can be regarded as the superposition of two bit streams of infinite ER. In these bit streams, which are designated as $P_{a1}(t)$ and $P_{a0}(t)$, the space-level is zero, as illustrated in Figs. 1(b) and 1(c). One bit stream is for the mark-level with a power level of P_1, and the other is for the space-level with a power P_0. The two bit streams have different optical carrier frequencies, f_1 and f_0, of which the difference corresponds to the adiabatic chirp. The right-hand side of Fig. 1 shows the spectrum for the corresponding bit stream. The spectrum of the superimposed bit streams [Fig. 1(a)] is the superposition of the spectra for the two bit streams [Figs. 1(b) and 1(c)]. Therefore, two peaks appear in the spectrum if the adiabatic chirp is large enough. The magnitude of each spectral peak is proportional to the average power of the bit stream; therefore the relative magnitude of the spectral peaks is equal to the ER of the directly modulated signals. When the effect of the transient chirp is included, it causes spectral broadening of each peak. The simplified model can well explain the chirp and the ER value for the signals after modulation and reshaping.

Applying optical filtering to the chirped spectrum can change the ER value and modify the chirping effects of a directly modulated signal, depending on the filter position and chirp characteristics. For example, an optical filter can be used to increase the ER of the modulated signal when the filter response is aligned to the mark-level spectral peak such that the space-level spectral peak is suppressed. On the other hand, a reduction in ER can be obtained by aligning the filter to the space-level spectral peak.

A good strategy for encoding data onto a DML is a combination of low ER modulation and optical filtering. This scheme can provide a large ER with reduced transient chirp. In the previous schemes, such as DST or CML, a very low ER value is required

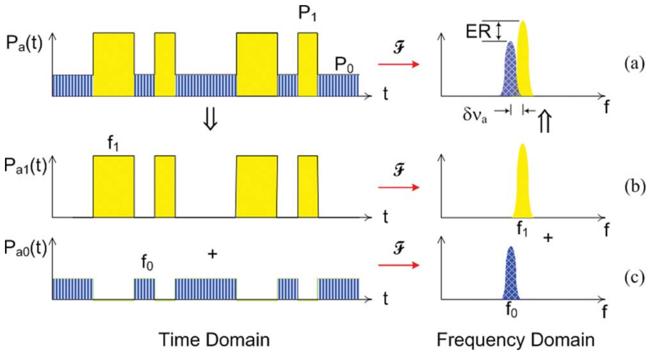

Fig. 1. Illustration of the bit stream with a finite ER adiabatic chirp as superposition of complimentary bit streams of infinite ER. The right-hand side shows the spectrum for the corresponding bit stream.

for the DML output signal; therefore an optical filter with a narrow and steep spectral response is needed to reshape the DML output signals to have a large enough ER and low chirp. This paper aims to extend the transmission distance of a DML for access network applications. To tolerate the operation condition and reduce cost, it is not preferred to use a filter with a steep spectral response. Some prior work detuned the laser spectrum to the slope of the filter response in order to obtain a larger suppression on the space-level spectral component [13,14]. However, this causes a larger insertion loss and unstable transmission characteristics. Instead, a good choice of optical filters to raise the ER is a single-cavity FP etalon with low to moderate finesse.

The choice of a FP etalon as the optical filter is also due to its periodic spectral response. When the FSR of an etalon matches the DWDM channel spacing, an etalon can provide reshaping to multiple channels. An array of DMLs can be first modulated with their own data of low ERs, combined with a wavelength multiplexer, and then reshaped by a FP etalon. This is very attractive for access applications, e.g., WDM passive optical networks, where DWDM lasers with direct modulation can be cost-effective solutions.

The ER improvement ΔER provided by the filtering with a single-cavity FP etalon can be obtained by calculating the relative suppression on the space-level spectral peak, assuming that the mark-level spectral peak is aligned to the peak of the filter response. From the transfer function of a FP etalon [22], the improvement is given by

$$\Delta \mathrm{ER} = 10 \log\left\{ 1 + \left(\frac{2F}{\pi}\right)^2 \sin^2\left(\frac{\pi}{F}\frac{\delta \upsilon_a}{f_{3\ dB}}\right)\right\} \quad \text{in dB}, \tag{4}$$

where F and $f_{3\ \mathrm{dB}}$ are the finesse and 3 dB bandwidth of the etalon, respectively. The finesse indicates the sharpness of the resonance mode. Figure 2 depicts the calculated ΔER against the ratio of adiabatic chirp over the 3 dB bandwidth of a FP etalon. In practice, the etalon bandwidth needs to accommodate the original signal spectrum (without chirp) to avoid the rise-time penalty caused by the intersymbol interference (ISI). As an example, a 10 Gbits/s nonreturn-to-zero (NRZ) signal requires about 15 GHz of filter bandwidth in considering the double-sideband spectrum. For the normal operation condition of a DML in DWDM access networks, the adiabatic chirp is usually less than 15 GHz. Therefore, the chirp-to-bandwidth ratio is typically less than 1.0 for 10 Gbits/s transmission. From Fig. 2, the ΔER is typically less than 6 dB by using a single-cavity FP laser for 10 Gbits/s DML links. Such an improvement might be enough for access networks. The improvement can be increased by using an optical filter with a flat-top transmission and steep edge transfer function, but this requires a relatively high-precision filter.

The ΔER obtained by using a simple FP etalon is relatively insensitive to the change in the finesse in cases where the chirp-to-bandwidth ratio is less than 1.0 as indicated in Fig. 2. For reshaping multiple DWDM channels, the finesse is in fact limited by the required FSR and 3 dB bandwidth. The FSR needs to match the channel spacing. For example, the finesse for reshaping 10 Gbits/s DWDM channels of 50 and 100 GHz channel spacing is about 3.3 and 6.6, respectively, if the FSR equals the channel spacing.

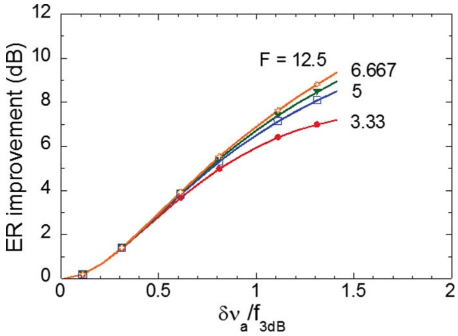

Fig. 2. ER improvement by using a single-cavity FP etalon.

3. Experimental Demonstration

3.A. ER and Chirp

TRC measurements are used to investigate the chirping effects and to optimize the laser operation condition. The DMLs used in the experiments have a threshold current and slope efficiency of about 10 mA and 0.11 W/A, respectively. The ER can be as large as 9 dB when it is driven with 18 mA of bias current and 40 mA of modulation current. The average output power at this condition is about 3.5 dBm. The FP etalon used in the experiment has a 3 dB bandwidth of about 0.125 nm (15 GHz) and a FSR of 100 GHz. Its finesse is 6.6. The etalon is coupled to the input/output fibers by using optical lenses, and its insertion loss is about 3 dB. The loss can be further reduced by using better alignment and packaging schemes.

Figures 3(a) and 3(b) show the measured chirp and effective α-value plotted against ER for different modulation currents, respectively. The ER is varied by adjusting the bias current. As expected, the transient chirp increases rapidly with a rising ER. For the case of smaller modulation current, the space-level is closer to the threshold condition of the laser in order to generate a given ER value. Therefore, the peak-to-peak chirp rises faster with an increasing ER for the 20 mA modulation case. The transient chirp can be over 40 GHz. The adiabatic chirp is slightly reduced as the ER rises. This is due to the fact that the adiabatic chirp coefficient in Eq. (3) is not a constant. As the bias is lowered to increase the ER, the relaxation resonant frequency of the laser drops and then affects the chirp characteristic [21]. The effective α-value is estimated from Eq. (1) by extracting the transient chirp, dP/dt, and $P(t)$ from the measured dynamic chirp and intensity waveform. The original α-value for the DML is about 4.5 at low ER modulation but varies with the laser operation conditions [23]. From Fig. 3(b), the α-value can be reduced to <1.0 by using the etalon filtering for the low ER cases. This indicates that the chirp reduction is due to not only the reduction in the slope of the signal transition but also a reduction in the effective α-value.

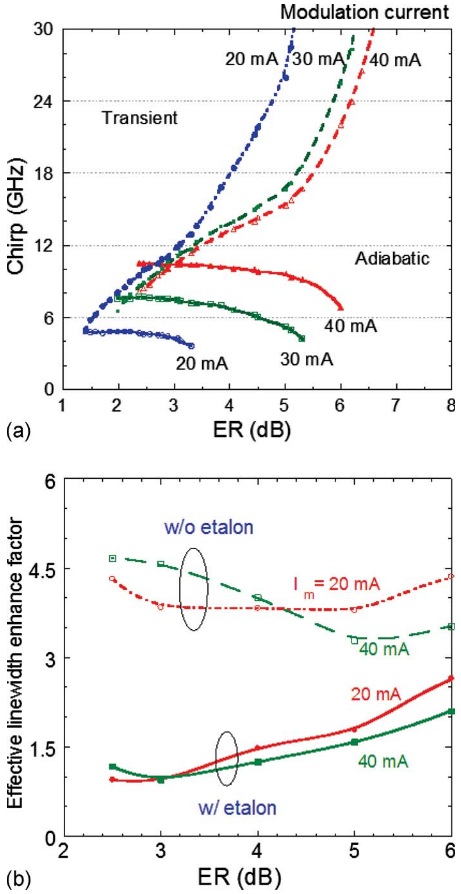

Fig. 3. Chirp characteristics versus ER. (a) Transient and adiabatic chirp and (b) effective α-value.

Figures 4(a) and 4(b) show, respectively, the chirp reduction and ER improvement by using a combination of low ER modulation and optical filtering. The transmission peak of the etalon is aligned to the spectral peak of the mark-level. Significant chirp reduction can be obtained by simply using a FP etalon. For example, to achieve an ER of 7 dB with 40 mA modulation, the resultant chirp is 31 and 15 GHz for the cases without and with etalon filtering, respectively. Therefore, adding an etalon after a DML can provide both ER improvement and chirp reduction, which leads to an increase in the transmission distance under dispersion-limit conditions [24].

The operation condition of a DML is usually limited by the maximal power of the mark-level and the modulation current. Modulating the laser with high bias and low ER is good for obtaining high output power, wide bandwidth, low transient chirp, and good spectral stability. Moreover, the timing jitter can also be reduced.

The results in Fig. 4(b) indicate that a FP etalon can provide a larger ER improvement when a larger modulation current (40 mA) is used. When the original ER is 3 dB, an ER improvement of about 2.6 and 3.9 dB can be obtained for 20 and 40 mA of modulation current, respectively. This is due to the fact that a larger modulation current generates a larger adiabatic chirp, which leads to a larger chirp-to-bandwidth ratio. Under such a condition, the optical filtering can suppress the space-level spectral peak to a larger extent. The results also indicate that the modulation with <5 dB ER can have <10 GHz frequency chirp after etalon filtering. Therefore, for access applications, the allowable ER can be higher than the aforementioned DST and CML schemes while the required finesse of the filter is only 6.6. On the other hand, for the 20 mA modulation cases, the chirp after filtering rises faster than the 40 mA modulation does due to the insufficient filtering. In particular, when the ER is >5 dB, the ER improvement by using the optical filtering is rather limited due to smaller adiabatic chirp but larger transient chirp. An optical filter with a larger slope in its spectral response is needed to enhance the ER improvement and chirp reduction for the low-modulation case.

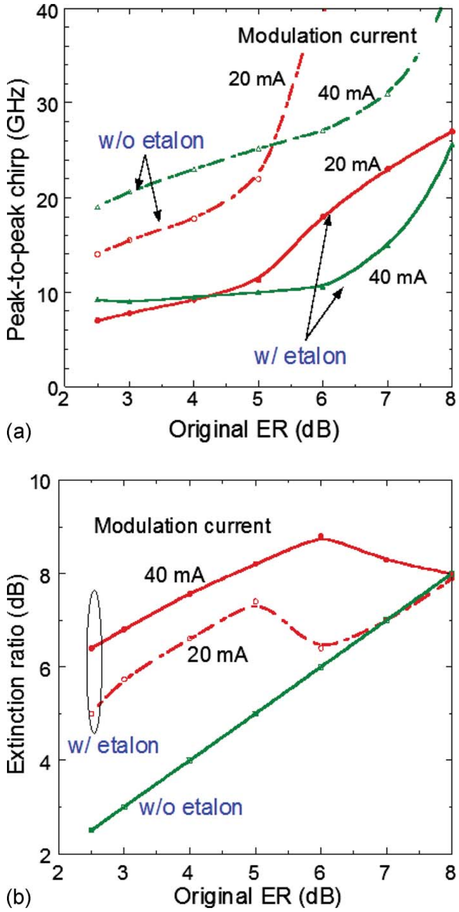

Fig. 4. (a) Chirp characteristics and (b) ER improvement versus the original ER value for the cases with or without filtering by a FP etalon.

3.B. Single-Channel Transmission

The DML is directly modulated at 9.95328 Gbits/s with a $2^{31}-1$ pseudorandom binary sequence (PRBS) signal. The modulation current is set as either 20 or 40 mA. The ER value is adjusted by controlling the bias current. Figure 5 shows the power penalty at a bit error rate (BER) of 10^{-9}. The signal is transmitted through a SMF. For the back-to-back (B2B) case, the major power penalty occurs at low ER conditions. By adding a FP etalon, the penalty can be reduced due to the improved ER.

Without adding an etalon to reshape the spectrum, the transmission distance is limited to 8.5 km with 3 dB of power penalty when the DML is modulated with an 8 dB ER as shown in Fig. 5(a). The distance can be increased with low ER modulation but suffers from a large power penalty. By adding an etalon the transmission distance can be extended to 75 km due to the chirp reduction. For further extending the transmission distance, a lower-ER modulation in conjunction with the DST and CML schemes can be used.

Figure 5(b) shows that the ER improvement is larger for the 40 mA modulation; therefore its power penalty for the B2B case is smaller compared to the 20 mA modulation case. Therefore, a larger adiabatic chirp can help to suppress the transient chirp of a DML by using the spectral reshaping scheme. Due to a larger suppression on the transient chirp, the 40 mA modulation case can tolerate an original ER up to 5 dB for a link span up to 50 km. In contrast, the 20 mA case can only tolerate <3.5 dB of ER. A larger tolerance on the ER value provides a larger flexibility in choosing the bias current and modulation current for operating the DML. However, it is the value of chirp rather than ER that determines the longest transmission distance. From Fig. 4(a), the postfiltering chirp at low ER (2.5 dB) condition is lower for

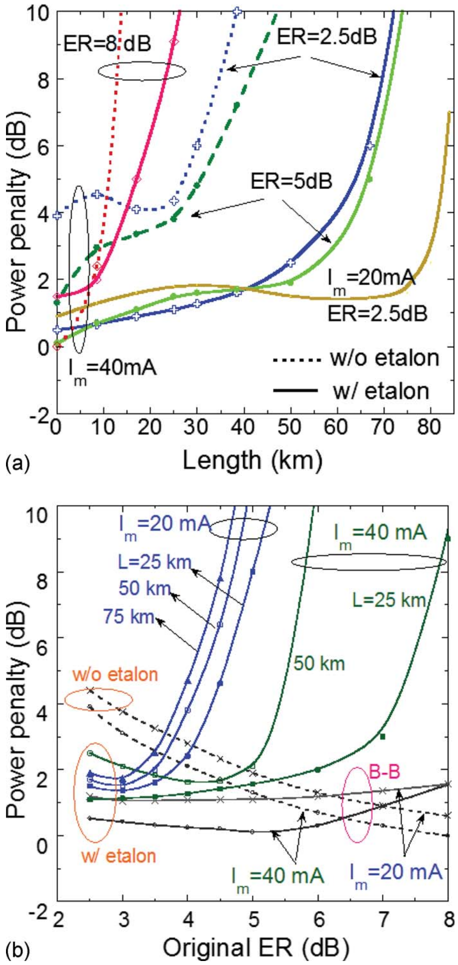

Fig. 5. Power penalty against (a) transmission length for various original ER values and (b) original ER value for various transmission distances. The modulation current is 40 mA in (a) except the one marked with 20 mA.

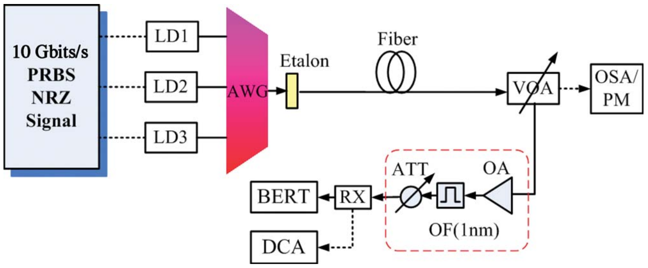

Fig. 6. Three-channel transmission; experimental setup.

the 20 mA modulation case; therefore it can transmit over a 75 km SMF that is longer than the 40 mA modulation case as shown in Fig. 5(a).

3.C. Multichannel Transmission

Three DMLs of 1539.93, 1550.13, and 1557.29 nm wavelengths are used to demonstrate the reshaping of multiple channels by a FP etalon with a finesse of 6.6. The 1539.93 nm channel is slightly off the designated wavelength grid because the FSR is 98 GHz for the etalon used in our experiments. The experimental setup is shown in Fig. 6. A modulation current of 40 mA is used to drive the lasers for transmission over 50 km. The AWG used in the experiments is a flat-top type with a 1 dB bandwidth of about 0.5 nm. A variable optical attenuator (VOA) is used to control the signal power level into the erbium-doped fiber amplifier (EDFA) in order to keep the optical signal-to-noise-ratio (OSNR) at 35 dB during the tests. An optical filter (bandwidth=1 nm)

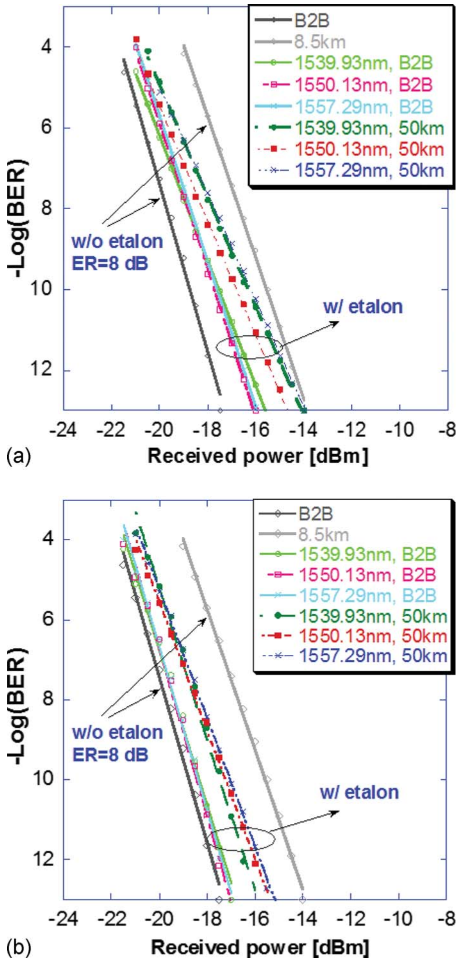

Fig. 7. BER performance for three-channel transmission when the original ER is (a) 2.5 dB and (b) 5 dB.

following the amplifier is used to reduce the amplified spontaneous emission (ASE) noise and to filter out one of the channels for BER measurements.

Applying a FP etalon after three DMLs can reshape the chirped optical spectrum to become narrow and symmetric for the three channels simultaneously. Figure 7 compares the BER between the cases with and without using an etalon at the transmitter. The performance of the B2B case with an 8 dB ER and no etalon is used as the baseline for comparison. When the original ER is 2.5 dB, Fig. 7(a) shows that the B2B power penalty for applying an etalon is almost 1.2 dB for the three channels, which is mainly due to an insufficient ER after applying the etalon. This is due to the fact that the etalon used in the experiment can provide only 3.8 dB of ER improvement. After 50 km transmission, the three channels have <2.2 dB of power penalty compared to the baseline. Figure 7(b) shows that the B2B power penalty for using the etalon is <0.5 dB for the three channels when the original ER is 5 dB. The B2B power penalty is smaller since the postfiltering signal has a larger ER (>8 dB). After 50 km of transmission, the three channels have <1.5 dB of power penalty. The results indicate that a FP etalon is effective to reshape signals of multiple channels to have very good performances.

4. Optimal Finesse and ER

Due to the finite ER improvement by a single-cavity FP etalon, there exist optimal parameters for the etalon and DML. The commercial VPItransmissionMaker WDM software [25] is used to simulate the power penalty by varying the ER of the DML and the 3 dB bandwidth of the etalon. The signal is transmitted over a 50 km SMF. The parameters of the DML and etalon are first chosen to approximate the above experimental results when the adiabatic chirp is 10 GHz and the finesse is 6.6. Then the finesse is varied for investigating the power penalty. The FSR of the etalon is 100 GHz. The etalon response is aligned to the mark-level spectral peak of the DML. The simulated results are shown in Fig. 8. Less than 1 dB of power penalty can be obtained when the 3 dB bandwidth of the etalon is between 15 and 20 GHz. This leads to the optimal values of finesse between 5.0 and 6.6.

When the 3 dB bandwidth is smaller than 15 GHz, the filtered signal is distorted due to insufficient bandwidth. On the other hand, an etalon with an overlarge (>20 GHz) 3 dB bandwidth cannot provide enough chirp reduction and/or ER improvement. The optimal original ER for the DML is around 4 dB, which is consistent with the experimental results shown in Fig. 5(b). When the original ER is too low (<3 dB), the power penalty increases since the postfiltering ER is not large enough. On the other hand, the transient chirp dominates the power penalty when the original ER exceeds 5 dB.

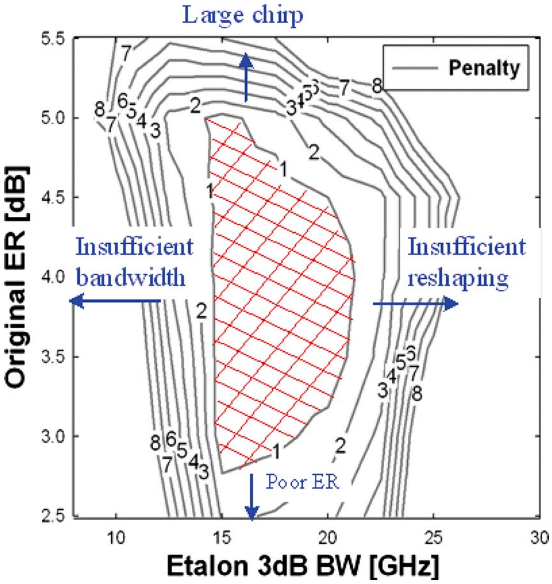

Fig. 8. Contour plot for the simulated power penalty versus the ER value and 3 dB bandwidth of the etalon.

5. Discussions and Conclusion

We demonstrated how to extend the transmission distance of multiple 10 Gbits/s directly modulated channels by simply adding a low-cost FP etalon after the lasers. The etalon has additional merits of periodic response, compactness, and easy packaging with the DML. Under the condition of midrange transmission distance in access networks, a low-finesse FP etalon can provide sufficient spectral reshaping to reduce the power penalty arising from chirp effects and low ER. The filter response is aligned to the mark-level spectral peak and thus results in a low-loss and stable operation condition.

Similar principles were demonstrated to enhance the ER for the downstream signals in a remodulation-type WDM passive optical network (WDM-PON) system by using a FP etalon at the receiver [26]. For the WDM-PON system, where the upstream signal is transmitted by remodulating the downstream signals, the downstream signals need to have low ER in order to reduce the cross talk to the upstream signals. By using the etalon, the downstream signals can have low ER so that the intensity fluctuation of the remodulated upstream signals can be reduced. For this application, the etalon mainly performs spectral reshaping to enhance the ER for the downstream signals. Though the principle is similar, the use of an etalon at the transmitter in this paper is mainly for reducing the laser chirp and expanding the transmission distance. Moreover, a single etalon can be used at the transmitter to reshape the signals from multiple DMLs.

The relationship among the laser chirp, ER, and the filter response is discussed in detail in this paper. The analytic formula of ER improvement is derived and agrees with these experimental data very well. Due to the limited ER improvement from a single-cavity etalon, there exist optimal ER values for the laser modulation and optimal finesse for the etalon. The resultant adiabatic chirp from the direct modulation needs to be compromised between the enhancement of spectral filtering and the maximal transmission distance. A large modulation current can be used to generate enough adiabatic chirp to enhance the ER improvement by using a FP etalon. Under such a modulation condition, larger tolerance on the ER value can be obtained. With an original ER of 5 dB, the link span can be extended from 8.5 to 50 km for multiple channels by simply using a single-cavity FP etalon.

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