

**Fig. 2** (a) Constructed experimental system setup. (b) Waveform of signal from BERT. (c) Waveform with overshoot after pre-emphasis driver. Different levels of pre-emphasis have different output waveforms.

20-nm-wide optical sources are transmitted through a second fiber to the RSOAs, with total fiber lengths between SLED and RSOAs of up to 1 km. The RSOA modulates the entire 20-nm-wide light source and reflects the signal back through the fiber, through the CWDM multiplexer, and back into the circulator. The circulator redirects the reflected signal into the receiver section of the central server station. The channels are separated again with another CWDM and fed into optical receivers. Finally, the data from all the remote sites are collectively analyzed by a central processor.

### 3 Experimental Setup

To demonstrate our proposed architecture, we built an experimental setup as shown in Fig. 2. For experimental purposes, we only populated one channel. The server site uses a SLED (DenseLight DL-BX9-CS5107A, Singapore) to provide the optical power needed for data transmission (8-mW total) and an APD-TIA receiver, which works at data rates up to 2.5 Gbps (OEMarket RX957, Sydney, Australia). The remote site contains the RSOA as the modulator (SOA-RL-OEC-1550 from CIP Technologies, IP switch, United Kingdom); the bit-error-rate tester as the data source [Anritsu (Richardson, Texas) 1632A BERT]; and a RSOA driver circuit, which is comprised of several key modules, as can be seen in Fig. 2(a).

The 3-dB frequency of the RSOA is only about 1.25 GHz. To achieve high quality data transmission at 2.5 Gbps, we used pre-emphasis, which is a technique that increases the amplitude of high frequency components of the signal, so that the entire system can achieve a higher bandwidth. The actual implementation of pre-emphasis is done in the time domain by adding an overshoot to the signal during transition; waveforms before and after application of pre-emphasis are shown in Figs. 2(b) and 2(c). Translated into frequency domain, the overshoot has the effect of amplifying the high frequency components. Overall, an RSOA is a low pass filter that rolls off around 1.25 GHz, but by integrating a pre-emphasis driver (which is a high pass filter) into the system, the overall frequency response is improved, allowing higher transmission data rates. In our RSOA driver circuit [Fig. 2(a)], we used a standard pre-emphasis driver (Maxim3982, Maxim, Sunny-

vale, California) after which the signal is further amplified by an rf amplifier [Marki (Morgan Hill, California) A08058]. Finally, the amplified rf signal is combined with a dc bias current in the bias-tee (Marki BT-0018) and coupled into the RSOA.

To evaluate the sensitivity of the optical system, a variable optical attenuator (VOA) [Thorlabs (Trenton, New Jersey) VOA50-APC] is used to attenuate the optical signal, which is then coupled into the APD-TIA receiver. The electrical output signals are fed back into the BERT to analyze the BER.

## 4 Experimental Results

The pre-emphasis driver provides four different levels of pre-emphasis, as shown in Fig. 2(c). Therefore, we first determined the optimal level of pre-emphasis for the system. Then, since several components are wavelength dependent, we studied the performance of each individual channel. Finally, we evaluated the effect of long distance transmission for the system. The performance of the optical link was evaluated with a pseudorandom bit sequence (PRBS) pattern with a length of  $2^{15}-1$  to represent radar data. The SLED output was measured as  $-0.72$ ,  $1.76$ ,  $2.79$ , and  $1.55$  dBm in the 1511, 1531, 1551, and 1571-nm CWDM channels, respectively. Power received by the RSOA is 5 dB below those levels caused by attenuation in the system. The RSOA was operated without temperature control with a bias current of 60 mA.

### 4.1 Performance Comparison of Pre-Emphasis Levels

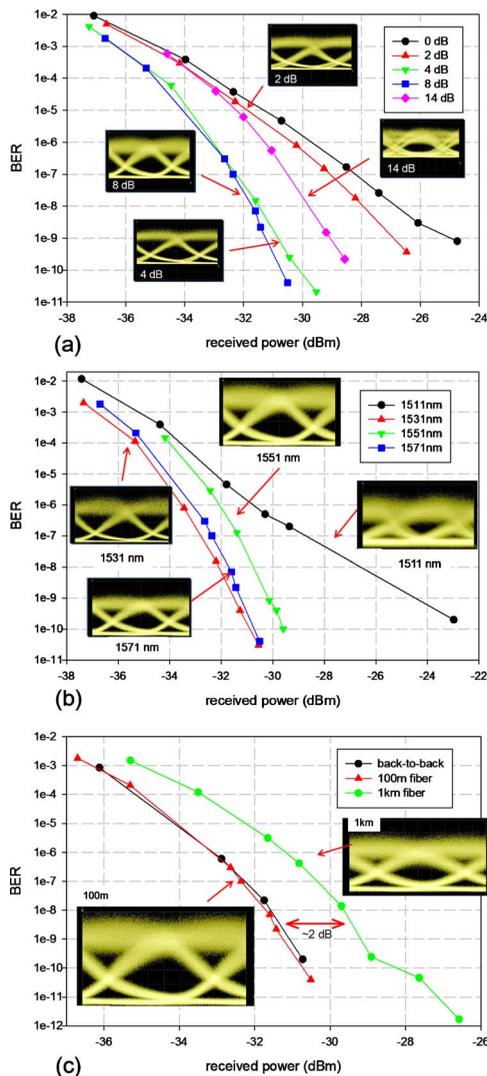
The four different levels of pre-emphasis are 2, 4, 8, and 14 dB. The performances of the four pre-emphasis levels were compared to a communication link with no pre-emphasis.

To analyze the performance of different pre-emphasis levels, the experimental system was set with a fiber length of 100 m, and the 1551-nm channel was activated. The eye diagrams and the sensitivity measurement results are shown in Fig. 3(a): 8- and 4-dB pre-emphasis are very similar and show the best performance, with a sensitivity improvement of about 6 dB (at  $10^{-9}$  BER) compared to the case without pre-emphasis. 2- and 14-dB pre-emphasis are only slightly better than no pre-emphasis. A pre-emphasis of 2-dB level is not sufficient, while a pre-emphasis of 14 dB overcompensates and leads to intersymbol interference (ISI), which can be seen as line doubling in the eye diagram. The sensitivity of the system using the optimal pre-emphasis level of 8 dB was measured as  $-31.5$  dBm.

### 4.2 Performance Analysis of Different Channels

Since 8-dB pre-emphasis provides the best performance, we kept this system parameter constant for further experiments to explore other system properties. The next key property we tested was the performance of the optical system for different CWDM channels: 1511, 1531, 1551, and 1571 nm.

The eye diagrams of the channels and the sensitivity of the channels are shown in Fig. 3(b). We observed no noise floor for all channels and better than  $10^{-12}$  BER perfor-



**Fig. 3** Eye diagram and sensitivity measurement results for (a) different pre-emphasis levels, (b) different channels; and (c) different transmission lengths.

mance was demonstrated at  $-10$  dBm received power by running the entire system for several hours with no errors detected.

The difference in the performance of the four channels can be explained with the wavelength-dependent SLED output and RSOA gain. Both are peaking around 1550 nm with a 3-dB bandwidth of about 60 nm. The performance drop in the 1511-nm channel is caused by the reduction of both SLED output and RSOA gain in that spectral region being the channel farthest from the maximum.

### 4.3 Transmission over 1 km of Fiber

With the performance of each channel identified, we measured the effect of fiber length on the performance of the communication link. The eye diagrams of the 1551-nm channel with 8-dB pre-emphasis transmitted over 100 m and 1 km of fiber are shown in Fig. 3(c). While the eye is still open at 100 m, it is beginning to close at 1 km. This is mostly caused by chromatic dispersion. The total dispersion  $\Delta t$  of a fiber link is  $\Delta t = D \cdot \Delta\lambda \cdot L$ , with  $D$  being the disper-

sion coefficient of the fiber,  $\Delta\lambda$  being the spectral bandwidth of the transmitted signal, and  $L$  being the link length. For our experiments, we used standard a single-mode fiber with  $D = 17$  ps/nm  $\times$  km. The bandwidth is determined by the 20 nm width of the CWDM channels. Therefore, the total dispersion of the 100-m link is 34 ps, and for the 1-km link it is 340 ps. By comparing to the eye width of about 400 ps at 2.5 Gbps, we expect much stronger signal deterioration at 1 km, as confirmed by the measured eye diagrams. Other effects that affect signal quality, e.g., attenuation, polarization mode dispersion (PMD), or nonlinearities, are not expected to influence this system and are not evident from the eye diagrams.

The BER performance measurement results are shown in Fig. 3(c). From the measurement data, we can see that the 100-m transmission system has similar properties compared to the back-to-back case. With 1-km transmission length, we measured a power penalty of 2 dB.

## 5 Conclusion

We develop a working prototype for a low-cost, high-speed RSOA-based optical connector for remote monitoring applications. We demonstrate that a 2.5-Gbps optical fiber communication link can be achieved with a SLED as light source and a directly modulated RSOA for data transmission on a CWDM channel roster. The concept of pre-emphasis for driving the RSOA is introduced to boost the data rate from the manufacturer specified 1.25 Gbps to 2.5 Gbps. Low BER data transmission is demonstrated for all four CWDM channels with a power penalty in the 1511-nm channel due to the present bandwidth limitations of optical components. Transmission over 100 m and 1-km distance is demonstrated, showing capability for in remote monitoring applications.

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