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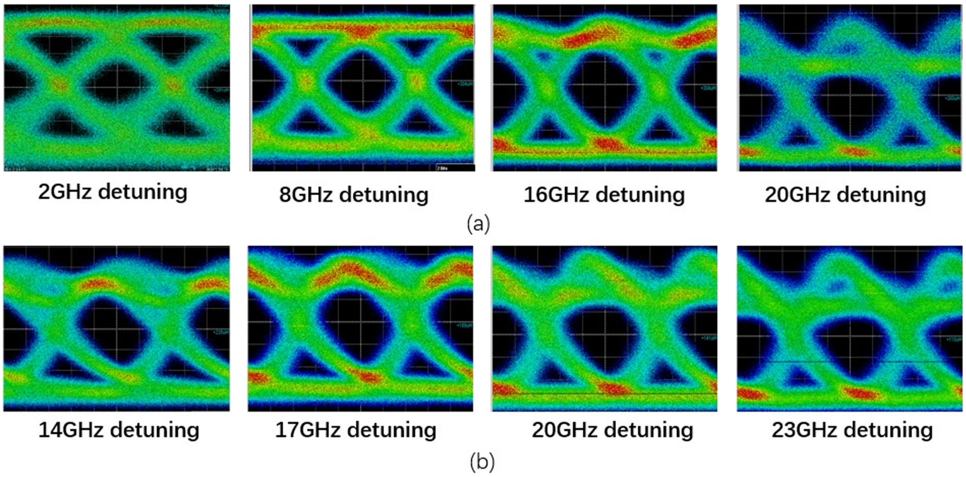

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Transmission Distance Extension of Directly Modulated Tunable V-cavity Laser Using AWG Wavelength Detuning

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Abstract: Directly modulated tunable lasers are highly desirable for constructing dense-wavelength division multiplexing (DWDM) access networks, owing to their advantages of low cost, compact size and low power consumption. However, the transmission distance for 10 Gbps is usually limited to about 10 km in the telecom C-band in standard single-mode fiber (SMF) due to wavelength chirp. Here we propose and demonstrate a simple technique for extending the transmission distance by detuning the wavelength of a tunable V-cavity laser with respect to DWDM multiplexers. Experiment results show that 10 Gbps signal can be transmitted error-free (BER$<10^{-12}$) over 20 km SMF with a wavelength-detuning with respect to a Gaussian-type arrayed waveguide grating (AWG) without dispersion compensation. The power penalty is only 1 dB compared to the back-to-back transmission.

Index Terms: Tunable laser, DWDM multiplexers, transmission distance extension.

1. Introduction

WDM passive optical networks (WDM-PON) are being upgraded from 2.5Gbps to 10Gbps to meet the rapid growth in internet traffic [1]. The next generation PON (NG-PON2) provides a downstream transmission of 40Gbps and upstream transmission of 10Gbps and have been studied extensively in order to meet the future requirements of bandwidth. TDM/WDM-PON, considered as the most attractive technology of NG-PON2, was achieved via stacking 4 wavelengths, each with 10Gbps data rate in the upstream and 2.5 Gbps in the downstream. Widely tunable lasers are the most desirable candidate to construct WDM-PON fiber access networks in order to reduce costs of inventory management and for dynamic bandwidth allocation. In the 10 Gbps WDM PON systems, over at least 20 km fiber transmission is needed. The dispersion of single-mode fiber (SMF) in the C-band induces signal degradations, causing increasing bit error rates (BERs) with increasing bit-rate and transmission distance. One method of eliminating the dispersion is to use dispersion compensation modules, which are bulky and bring additional cost. For high-speed long-distance systems, electro-absorption modulator and Mach-Zehnder modulator are still the dominant choices.

However, the external modulators are expensive, and have high energy consumption. Therefore, for access networks, low cost, compact, low power consumption tunable transmitters requiring no extra dispersion compensation are highly desirable.

Optical duo-binary [2], phase shaped binary transmission [3], and optical field pre-distortion [4] are the dispersion tolerant technologies for extending transmission distance. However, these solutions need signal pre-processing and costly $LiNbO_3$ external modulator with high power consumption. Direct modulation schemes with small size, low power consumption and low cost have attracted increasing attention in 10 Gbps WDM transport systems. However, the transmission distance and transmission speed of direct modulation are limited by their intrinsic frequency chirp [5]. For 10 Gbps transmission, only several kilometers over single mode fiber can be reached without dispersion compensation in the C-band. Chirp managed lasers (CMLs) with transmission distance over 200 km have been demonstrated, where directly modulated lasers are followed by optical filter [6]. The principle of chirp managed laser is converting the adiabatic chirp frequency modulation (FM) to increased amplitude modulation (AM) to generate dispersion-tolerant high extinction ratio signals through the edge filtering effect [7], [8]. CMLs commonly use a distributed feedback laser and a multi-cavity filter [9]. Tunable lasers and optical filters working together as CMLs have also been demonstrated. A compact DFB-array-based CML module with 30-nm tuning at 10 Gbps was reported [10], [11]. A transmitter consisting of a frequency-modulated widely tunable super-structure-grating distributed Bragg reflector (SSG-DBR) laser and an optical filter was also reported [12]. Full-C-band tunable Modulated-Grating Y-branch (MGY) chirp managed laser was used to demonstrate 10 Gbps error-free 200km transmission in the form of small form factor XFP [13]. Fiber Bragg Gratings [14], multi-cavity thin film filters [15], micro-ring resonator (MRR) [16–18] or double-slanted-trench resonant tunneling structure (DST-RTS) [19] were employed as optical filters, which increased the complexity and cost of the systems.

In this paper, we propose and demonstrate a simple technique for extending the transmission distance by detuning the wavelength of a tunable V-cavity laser with respect to the arrayed waveguide grating (AWG) which is used as the multiplexer in the system. Thus, no additional filtering device is needed. We experimentally investigate the impact of the wavelength detuning on the transmission performance using a directly modulated tunable V-cavity laser packaged in SFP+ module at 10 Gbps [20], [21] and a commercially available array waveguide grating (AWG). Experiment results show the signal can be transmitted error-free (BER $< 10^{-12}$) over 20 km SMF without dispersion compensation and there is an optimal frequency detuning producing the best eye diagram and BER performance.

2. Experimental Setup and Operation Principle

The experimental setup of the transmission test is shown in Fig. 1. The V-cavity laser packaged in the form of SFP+ was directly modulated at 10 Gb/s with a $2^{31}-1$ non-return-to-zero (NRZ) pseudo-random binary sequence (PRBS) signal generated by pulse pattern generator (PPG) in the BERT (Bit Error Rate Tester). The bandwidth of the V-cavity laser is about 8 GHz. The V-cavity laser based SFP+ module has 7 dBm output power and is tunable over 16 ITU channels from Ch. 21 (192.10 THz) to Ch. 36 (193.60 THz). The optical signal was then fed into a commercial Gaussian-type AWG which has 40 channels from Ch. 18 (191.80 THz) to Ch. 57 (195.70 THz) with 100 GHz channel spacing and 30 GHz 3 dB-bandwidth. The laser wavelength was tuned to the AWG channels with varying detuning during the experiments. After passing through the AWG, the signal was either connected to the receiver (back to back) or transmitted over 10 km or 20 km SMF. At the end of the link, the signal was attenuated, detected by the receiver of the SFP+ and analyzed in the BERT for bit-error-rate and eye diagram measurements. The variable optical attenuator (VOA) is used to adjust the input power of the receiver. The transmission performance was compared based on the above measurements for 0, 10 km and 20 km SMF without and with the AWG filtering in every channel.

As shown in Fig. 2, taking one particular channel (192.1 THz) as an example, the center wavelengths of V-cavity laser and AWG were the same in the initial state. The green trace corresponds

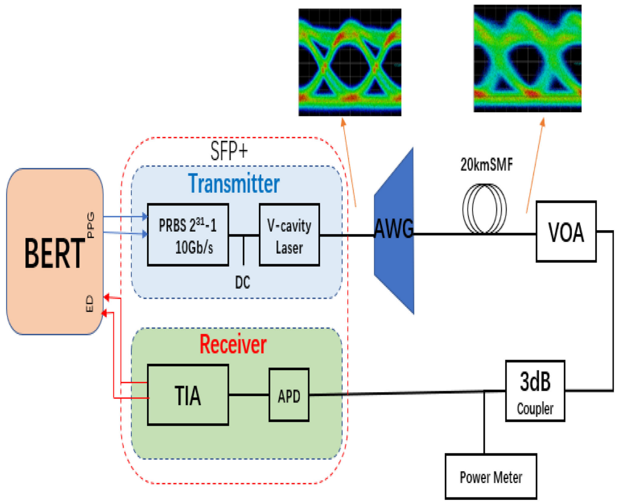

Fig.1. Measurement setup and eye diagram before AWG and after 20 km SMF transmission.

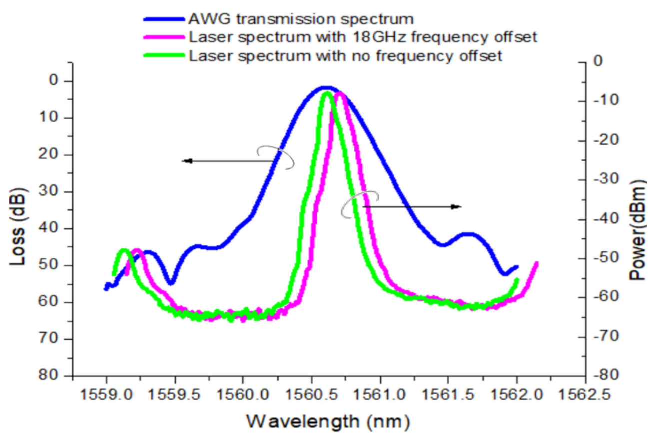

Fig. 2. AWG transmission spectrum, laser spectrum with/without frequency detuning.

to the V-cavity laser spectrum and the blue trace corresponds to the AWG transmission peak. The frequency of the tunable V-cavity laser was then detuned to the longer wavelength side of the AWG peak. Since the '1' state has a higher carrier injection resulting in a lower refractive index, its wavelength is blue-shifted with respect to the '0' state. As a result, the transmission of the blue shifted '1' state is enhanced while the '0' state is suppressed, resulting in a higher extinction ratio. Besides, similar to conventional CMLs [6], the rise and fall times of the chirp waveform are significantly reduced by the detuned AWG so that the wavelength (or frequency) is essentially constant for the duration of the '1' bits including the transitions, which effectively reduces the wavelength chirp. Furthermore, under optimal chirp management conditions, two '1' bits separated by a '0' bit can be π out of phase, resulting in a destructive interference in the overlapped pulse tails after fiber transmission, thus making the chirp managed signal tolerant to fiber dispersion [6]. The output frequency of V-cavity laser can be shifted 15 GHz per 1 °C temperature change through the TEC control of the laser. There is an optimal frequency offset where the best performance is achieved, which is dependent on the transmission distance.

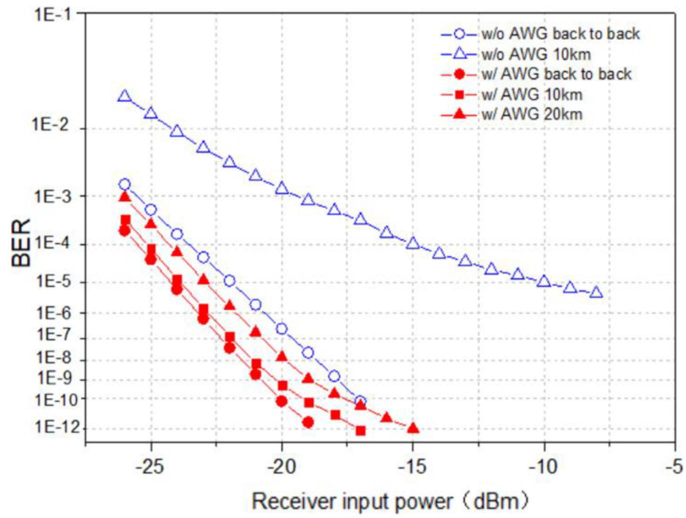

Fig. 3. BER performance at 10 Gb/s for back-to-back and after transmission over 10 km and 20 km SMF with and without AWG filtering.

3. Results and Discussion

First, we investigate the transmission without dispersion compensation in one particular channel (192.1THz). The different transmission performances between with and without AWG filtering were compared in three cases: back-to-back,10 km and 20 km, as shown in Fig. 3. The BER performance improvement was evident after AWG edge filtering effect. Considering the back-to-back situation without AWG filtering, the receiver sensitivity, defined as the received power required for error-free transmission (BER $< 10^{-12}$), was about -16 dBm. The receiver sensitivity of the back-to-back situation with detuned AWG filtering was improved by approximately 3 dB with a frequency detuning of about 10 GHz.

After transmission over 10 km or 20 km SMF, the accumulated dispersion degraded significantly the quality of the received signal. Without the AWG filtering, an error floor appeared for 10 km SMF transmission at -7 dBm received power above a BER $= 10^{-6}$. The BER performance for 20 km SMF transmission was even worse and not shown in Fig. 3. In the case with the AWG filtering, the power penalty at BER $= 10^{-12}$ was only 2 dB for 10 km SMF transmission and 4 dB for 20 km SMF transmission, compared to back-to-back with AWG filtering. They are comparable or even better than the back-to-back case without AWG filtering. Therefore, by using the frequency detuned AWG filtering, the signal quality after fiber transmission can be restored or even improved with respect to back-to-back case, without any dispersion compensation module. The optimal frequency offsets are around 10 GHz for back to back, 15 GHz for 10 km SMF transmission, and 20 GHz for 20 km SMF transmission. Note that the output power of the VCL is around 7 dBm, and varies very little with the wavelength detuning. The insertion loss of the Gaussian AWG is about 2.3 dB at the central channel wavelength, and increases to 3.3 dB, 4.5 dB and 6 dB, respectively, for 10 GHz, 15 GHz, and 20 GHz detuning. The corresponding output power after the AWG are therefore 3.7 dBm, 2.5 dBm, and 1 dBm, respectively.

The initial extinction ratio of the signal is around 3.2 dB. The extinction ratio of the signal after the AWG filtering increases to 3.4 dB, 3.5 dB and 3.7 dB with 10 GHz, 15 GHz, and 20 GHz frequency detuning, respectively. Fig. 4 shows the eye diagrams after transmission over 10 km and 20 km SMF with AWG filtering. The frequency detuning for 10 km SMF transmission is from 2 GHz to 20 GHz in 6 GHz step and the frequency detuning for 20 km SMF transmission is from 14 GHz to 23 GHz in 3 GHz step. In both cases, as the frequency detuning increases, the eye

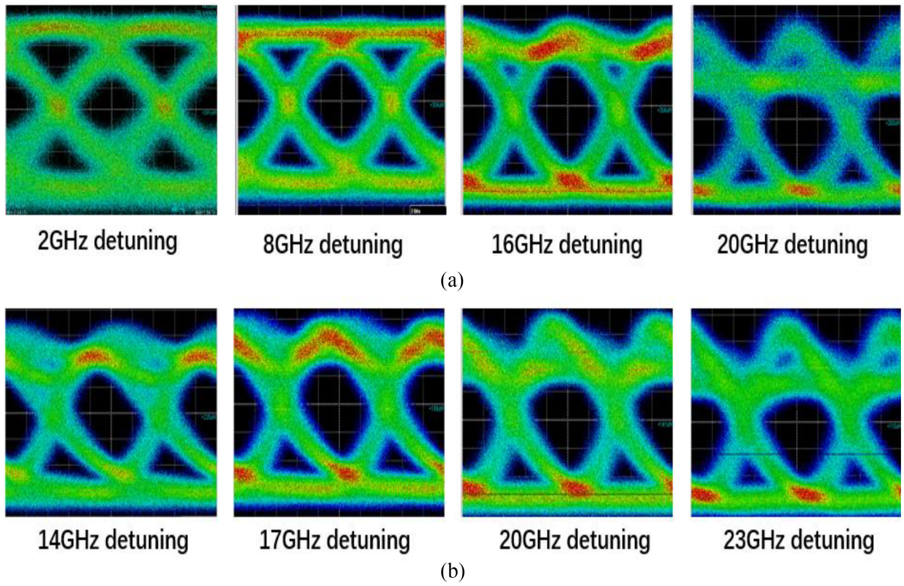

Fig. 4. Eye diagrams for different frequency detuning after transmission over 10 km (a) and 20 km (b) SMF with AWG filtering.

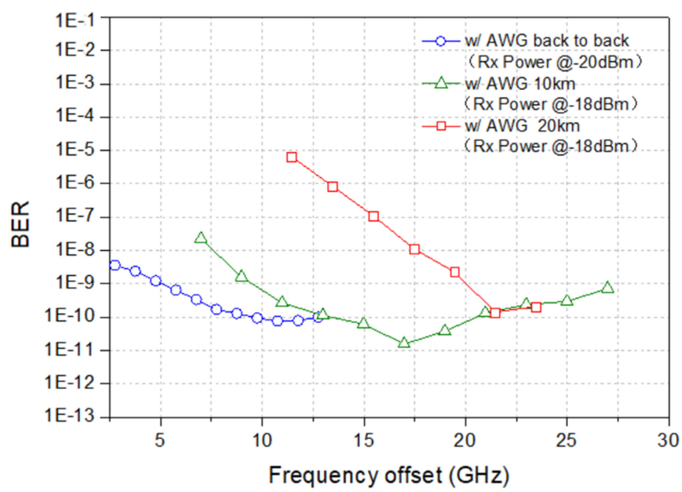

Fig. 5. BER versus frequency detuning for three different transmission distances.

diagram opening increases first and then decreases. There is an optimal detuning where the best eye diagram is achieved.

Similarly, the BER performance is also dependent on the amount of the frequency detuning, and the optimal detuning is dependent on the transmission distance. Fig. 5 shows the BER as a function of the frequency detuning of the laser with respect to the center frequency of the AWG filter. The BER of the system is the lowest when the frequency detuning is 11 GHz, 16 GHz and 21 GHz, respectively, for back-to-back, 10 km and 20 km transmission distances.

The transmission performance is affected by the adiabatic chirp of the laser, similar to conventional CMLs [6]. In principle, by increasing the bias current and setting the adiabatic chirp to approximately half of the bit rate, the inter-symbol interference of the signal can be made destructive and the transmission performance can be improved. The specific value of adiabatic chirp was not

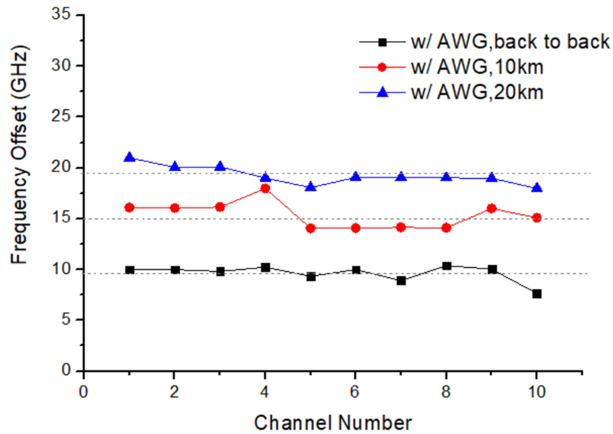

Fig. 6. Optimal frequency detuning for different channels with AWG filtering for back-to-back, 10 km transmission and 20 km transmission.

measured due to our equipment restriction. In our experiment, we optimized the bias current based on eye-diagram and BER measurement.

The above transmission results, without dispersion compensation, confirm the effectiveness of using frequency detuning with respect to the AWG central frequency to extend the transmission reach with the directly modulated laser. To further demonstrate the effectiveness of the technique for all the channels of the directly modulated tunable V-cavity laser, we performed the transmission experiments for 10 consecutive channels. The frequencies of these channels are from 192.1 THz to 193.0 THz and the channel spacing is 100 GHz. The BER performance and optimal frequency offsets are recorded for back-to-back, 10 km SMF and 20 km SMF transmission. Fig. 6 shows the optimal frequency detuning of all channels for different transmission distances. The optimal frequency detuning is clearly dependent on the transmission distance, while the variations across different channels are relatively small considering the measurement errors. The optimal frequency offsets of the ten channels are around 10 GHz for back to back,15 GHz for 10 km SMF transmission, and 20 GHz for 20 km SMF transmission.

Note that we use the AWG multiplexer already existing in the system to do the chirp management. It is not specially designed for chirp management as compared to the filter used in CMLs. The 3 dB bandwidth of our AWG is about 34GHz, wider than that of the CML filter which is usually below 10 GHz. The slope of our AWG is about 0.34 dB/GHz at the detuning frequency point, which is less steep than that of the CML filter (typically larger than 2 dB/GHz). As a result, the required wavelength detuning is larger. However, with an appropriate detuning, these characteristics are sufficient to extend the transmission distance of the DML to 20 km required for access networks, without the complexity of integrating a filter in the laser package as in the case of CMLs.

4. Conclusion

In conclusion, we have demonstrated the effectiveness of extending the transmission distance of directly modulated tunable VCL lasers by using frequency detuning with respect to a Gaussian-type array waveguide grating multiplexer. The frequency detuning converts the chirp-induced frequency modulation to useful amplitude modulation to improve the transmission performance. Experimental results show that 10 Gbps signal can be transmitted error-free (BER $< 10^{-12}$) over 20 km SMF without any dispersion compensation. By using the frequency detuned AWG filtering, the signal quality after fiber transmission can be restored or even improved with respect to back-to-back case. As compared to conventional techniques for chirp managed lasers, no additional filtering component is required. Therefore, the technique holds promise for low cost DWDM networks.

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