IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 7, Number 1, February 2015

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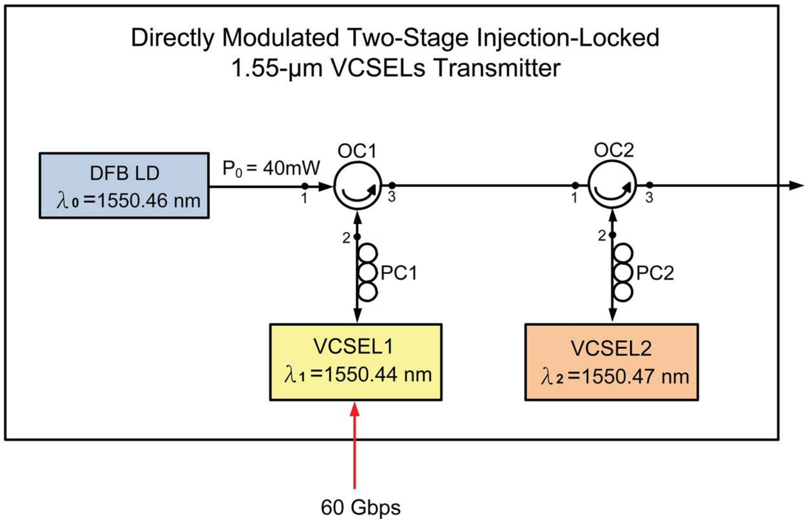

DOI: 10.1109/JPHOT.2015.2395147
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A 20-km/60-Gb/s Two-Way PON Based on Directly Modulated Two-Stage Injection-Locked 1.55-μm VCSEL Transmitters and Negative Dispersion Fibers

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DOI: 10.1109/JPHOT.2015.2395147
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Manuscript received December 17, 2014; revised January 16, 2015; accepted January 18, 2015. Date of publication January 23, 2015; date of current version February 12, 2015. This work was supported by the Ministry of Science and Technology of the Republic of China under Grant MOST 101-2221-E-027-040-MY3, Grant MOST 103-2218-E-027-001, and Grant MOST 103-2218-E-027-011. Corresponding author: H.-H. Lu (e-mail: hhlu@ntut.edu.tw).

Abstract: A 20-km/60-Gb/s two-way passive optical network (PON) based on directly modulated two-stage injection-locked 1.55-μm vertical-cavity surface-emitting laser (VCSEL) transmitters and negative dispersion fibers (NDFs) is proposed and demonstrated. A one-stage injection-locked technique has been confirmed as an effective approach for increasing the frequency response of a VCSEL. A two-stage injection-locked technique, which can further increase the frequency response of a VCSEL, is thereby expected to have excellent transmission performance in a two-way PON. To be the first to employ directly modulated two-stage injection-locked 1.55-μm VCSEL transmitters in a two-way PON, brilliant bit-error-rate performance and a clear eye diagram are obtained over a 20-km NDF transport. A directly modulated VCSEL has a positive chirp, whereas an NDF has a negative dispersion property in the transmission fiber; this negative dispersion property compensates the laser positive chirp and results in systems with better transmission performance. Such an innovative two-way PON provides the advantage of a communication link for high data rates, which is an attractive feature that is useful for broadband network applications.

Index Terms: Negative dispersion fiber (NDF), passive optical network (PON), two-stage injection locked, vertical-cavity surface-emitting laser (VCSEL).

1. Introduction

With the continuous increase in the demand for communications, optical networks will need to be even more ubiquitous than they are today. Passive optical network (PON) has been drawing increasing attention as a practical option for a next-generation broadband network because of mature optical technologies. PON is the most promising candidate for lightwave network because of its network security, easy maintenance, and significant flexibility [1], [2]. For a practical implementation of PON, however, high-speed data access is the primary concern of system designers. Vertical-cavity surface-emitting laser (VCSEL) technology has recently had significant developments, such that VCSEL can be designed to operate in the 1.55-μm wavelength window under a single transverse mode. The 1.55-μm VCSEL has evolved as an emitter for high-speed data communication owing to its narrow coherent beam [3]. The new generation of VCSEL scheme is optimized for modulation bandwidth of up to a few tens of GHz. One of the promising schemes is the two-stage injection-locked VCSELs. Two-stage injection-locked VCSELs integrate the optical properties and advantages of VCSELs and open an innovative and promising method of high-speed operation, in which the bandwidth bottleneck of conventional laser diodes (LDs) is overcome [4]. One-stage injection-locked technique has been verified as an effective approach for enhancing the frequency response of VCSEL [5]. Two-stage injection-locked technique, which can further enhance the frequency response of VCSEL, is thereby expected to have excellent transmission performance in PON. A directly modulated transmitter has recently become attractive for PON applications because such transmitter costs lower than an externally modulated transmitter. However, a directly modulated transmitter has large chirp, which limits the transmission distance because of small dispersion tolerance. The interaction of fiber chromatic dispersion with the chirp of the directly modulated transmitter is one of the most severe limiting factors of a two-way PON. Such limitation causes intolerable amounts of distortions. Therefore, a dispersion compensation device should be used to overcome the dispersion effect and consequently decrease the distortions. Negative dispersion fiber (NDF), which has a negative dispersion characteristic, is expected to compensate for the positive laser chirp and improve the dispersion tolerance in a directly modulated PON [6], [7]. In this paper, a 60-Gbps two-way PON based on directly modulated two-stage injection-locked 1.55-μm VCSELs transmitters and NDFs is proposed and experimentally demonstrated. We successfully demonstrate that a 60-Gbps data stream can be directly modulated and transmitted up to a maximum of 20 km NDF. Generally, the NDF is not cheaper than SMF and is not popular to be installed in the PON. However, the fiber length needed to install in the PON is quite short (20 km) and an amateur can deploy it with minimal training. Instead of employing a trained person with high-precision devices to deploy SMF, the NDF will be a promising candidate for installing. The NDF is worth deploying due to its negative dispersion characteristic to compensate for the positive laser chirp and improve the transmission performance of a directly modulated PON. To be the first one of employing directly modulated two-stage injection-locked 1.55-μm VCSELs transmitters and NDFs in a 20 km/60 Gbps two-way PON, brilliant bit error rate (BER) performance and clear eye diagram are achieved. Such a directly modulated two-stage injection-locked 1.55-μm VCSELs transmitters and NDFs-based two-way PON offers the advantage of a communication channel for high data rates, which is quite useful for broadband network applications.

2. Experimental Setup

The architecture of the proposed 20 km/60 Gbps two-way PON based on directly modulated two-stage injection-locked 1.55-μm VCSELs transmitters and NDFs is shown in Fig. 1. The transmitter is directly modulated by a 60-Gbps pseudorandom binary sequence (PRBS) of $2^{23} - 1$. The modulated light is attenuated by a variable optical attenuator (VOA), transmitted through an NDF link, and then reaches a 60-GHz photodiode (PD). System links with different transmission lengths of 0 km to 20 km NDF, with an attenuation of 0.212 dB/km and a negative dispersion of -2.2 ps/nm/km. The high-bandwidth PD has a detection wavelength range of 860 nm to 1630 nm, with a responsivity of 0.7 mA/mW at 1550 nm and a 3-dB bandwidth of 60 GHz. The received data signal is then amplified by a 60-GHz low noise amplifier (LNA) with a noise figure of approximately 3.4 dB. The data are recovered by a data recovery scheme and fed into a BER tester (BERT) for BER performance evaluation. The LNA is important in amplifying the 60-Gbps data stream while adding as little noise and distortion as possible. For the data recovery scheme, the receiving site generates a clock from an approximate frequency reference, phase-aligns to the transitions in the data stream, and thus regenerates the data stream.

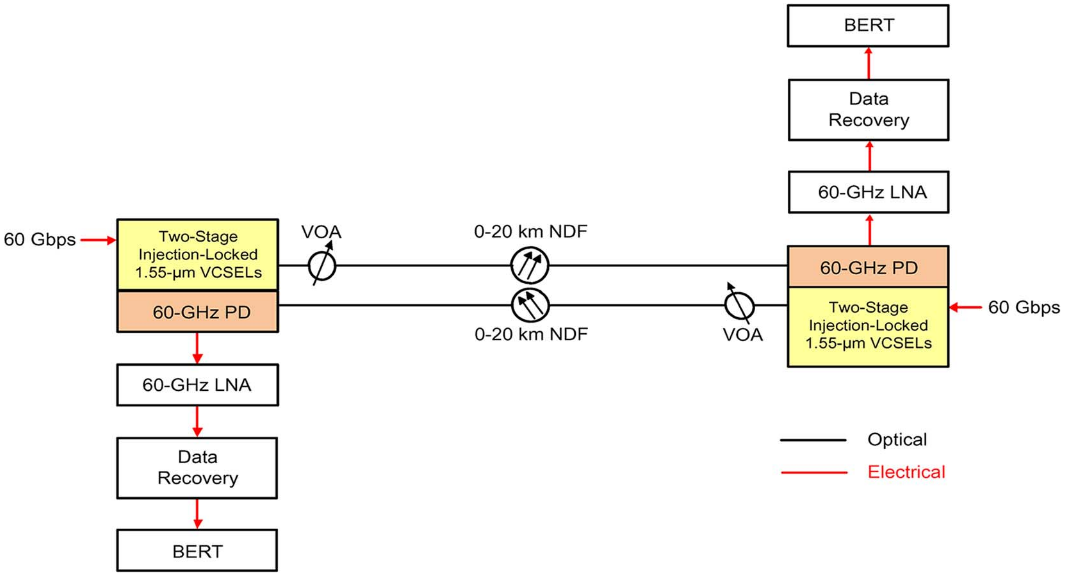

Fig. 1. Architecture of the proposed 20 km/60 Gbps two-way PON based on directly modulated two-stage injection-locked 1.55-μm VCSELs transmitters and NDFs.

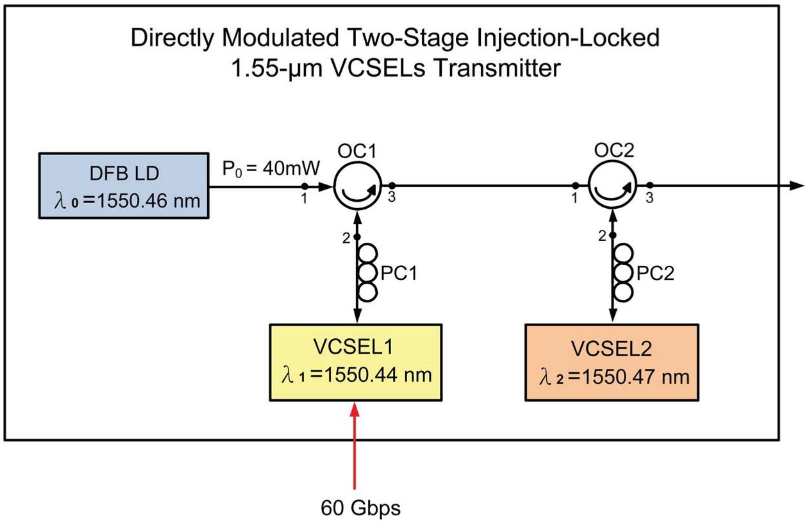

Fig. 2. Configuration of the directly modulated two-stage injection-locked 1.55-μm VCSELs transmitter.

The configuration of the directly modulated two-stage injection-locked 1.55-μm VCSELs transmitter is presented in Fig. 2. A distributed feedback (DFB) LD, with an optical power of 40 mW and a central wavelength of 1550.46 nm (λ_0), is employed as the master laser. The 60-Gbps data stream is directly fed into VCSEL1, with a central wavelength of 1550.44 nm (λ_1). The optical output of DFB LD is injected into VCSEL1 via an optical circulator (OC1) and a polarization controller (PC1) at an injection ratio of around 10 dB. Meanwhile, VCSEL2, with a central wavelength of 1550.47 nm (λ_2), is injection locked by VCSEL1 via OC2 and PC2 at a strong injection ratio of around 14 dB. The three-port OC is worth employing due to excellent optical characteristics, including low insertion loss ($\sim$0.7 dB), high isolation ($>$ 42 dB), and environment stability. The PC is utilized to match the master polarization to the VCSEL preferred polarization to firm up the locking stability. The frequency response of the two-stage

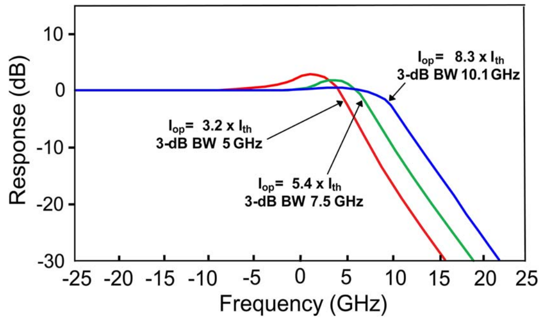

Fig. 3. Frequency response of the free-running VCSEL1.

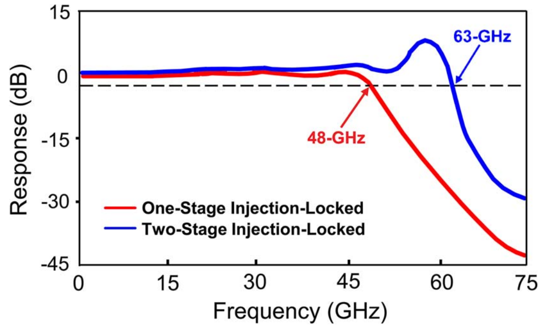

Fig. 4. Frequency responses of the one-stage/two-stage injection-locked 1.55-μm VCSEL(s).

injection-locked 1.55-μm VCSELs transmitter is measured at port 3 of OC2 by using an optical network analyzer.

3. Experimental Results and Discussion

The VCSEL works under single transverse mode at 1.55 μm with buried tunnel junction structure designed for high-speed operation, thereby providing a promising method by which to achieve excellent performance in a high-speed two-way PON. The frequency response of the free-running VCSEL1 is shown in Fig. 3. Given that the operation current (I_{op}) is operated at 8.3 times the threshold current (I_{th}), the 3 dB bandwidth is about 10.1 GHz. This finding indicates that VCSEL is designed for efficient use in high-speed data communication. Both VCSELs (VCSEL1 and VCSEL2) have the same frequency response characteristics.

The outer boundary of the locking range for a VCSEL under light injection is given by [8]

$$d < \pm \frac{k_c}{2\pi}\sqrt{\frac{S_i}{S(1+\alpha^2)}} \tag{1}$$

where d is the frequency detuning, k_c is the coupling coefficient, S_i/S is the injection ratio, and α is the linewidth enhancement factor. Within the locking range, the injection-locking behavior happens. However, outside the locking range, severe oscillation occurs. As the optimal injection locking happens, system has the best transmission performances in terms of the lowest received optical power level (as BER is 10^{-9}) and the minimum amplitude fluctuation in the eye diagram.

The frequency responses of the one-stage injection-locked 1.55 μm VCSEL and two-stage injection-locked 1.55-μm VCSELs are presented in Fig. 4. The 3-dB bandwidth is one of the important figures-of-merit that characterize the performance of VCSEL. For one-stage injection-locked 1.55-μm VCSEL, the 3-dB bandwidth is 48 GHz. For two-stage injection-locked 1.55-μm VCSELs, the 3-dB bandwidth is increased up to 63 GHz as expected. This finding suggests that the two-stage injection-locked 1.55-μm VCSELs transmitter is strong enough for 60 Gbps

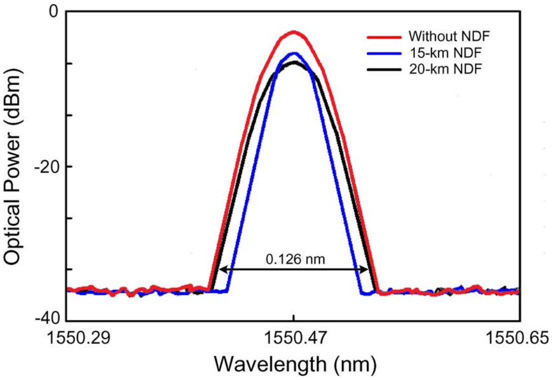

Fig. 5. Optical spectra for a directly modulated two-stage injection-locked VCSELs transmitter with and without NDF transport.

transmission. To obtain high 3-dB bandwidth, the wavelengths of the injected lights should be carefully selected to achieve the optimal enhancement in the frequency response of the two-stage injection-locked VCSELs. For the first-stage injection locking, the wavelength of the master laser (DFB LD) should be slightly longer than that of the slave laser (VCSEL1) to obtain a flat frequency response; that is, positive wavelength detuning is employed to achieve the first-stage injection locking. For the second-stage injection locking, however, the wavelength of the master laser (one-stage injection-locked VCSEL1) should be slightly shorter than that of the slave laser (VCSEL2) to obtain a high-frequency resonance peak; that is, negative wavelength detuning is employed to achieve the second-stage injection locking [9].

Meanwhile, the second slave laser (VCSEL2) needs to be injection locked at a strong injection [10]

$$f_r^2 \cong f_0^2 + k^2\left(\frac{A_{\text{inj}}}{A_0}\right)^2 + \sin^2\phi_0 \tag{2}$$

where f_r is the resonance frequency of the injection-locked laser, f_0 is the relaxation frequency of the free-running slave laser, k is the coupling coefficient, A_{inj}/A_0 is the injection ratio, and ϕ_0 is the phase difference between the injection-locked slave laser and the master laser. As shown in (2), the resonance frequency of the injection-locked laser is proportional to the square of the injection ratio. Therefore, strong injection results in high resonance frequency.

The optical spectra for a directly modulated two-stage injection-locked VCSELs transmitter with and without NDF transport are shown in Fig. 5. It can be seen that originally the optical signal possesses a wide 0.126 nm spectral linewidth, as spectral linewidth is defined in term of the linewidth at 40 dB away from peak power. Over a-15 km NDF transport, the optical signal possesses a narrow 0.098 nm spectral linewidth; over a-20 km NDF transport, the optical signal possesses a 0.125 nm spectral linewidth. The broadened optical spectrum by the positive chirp of directly modulated two-stage injection-locked VCSELs transmitter is compressed by the negative dispersion of NDF, by which leading to an improvement of dispersion tolerance.

In a direct modulation scheme incorporating a VCSEL with positive chirp parameter$\Delta\upsilon$, the second-order harmonic distortion-to-carrier ratio $(\mathrm{HD_2/C})$ and third-order intermodulation distortion-to-carrier ratio $(\mathrm{IMD_3/C})$ can be expressed as [11]:

$$\frac{\mathrm{HD_2}}{\mathrm{C}} = \frac{1}{4}m\ddot{\beta}L\Omega\sqrt{(4\cdot\Delta\upsilon)^2 + (\ddot{\beta}L\Omega^3)^2} \tag{3}$$

$$\frac{\mathrm{IMD_3}}{\mathrm{C}} = -\frac{9}{32}(m\ddot{\beta}L\Omega)^2\left[4\cdot(\Delta\upsilon)^2 + \Omega^2\right] \tag{4}$$

where m is the optical modulation index, $\ddot{\beta}$ is the second-order dispersion coefficient, L is fiber length, and Ω is the RF signal carrier frequency. A direct method by which to reduce positive

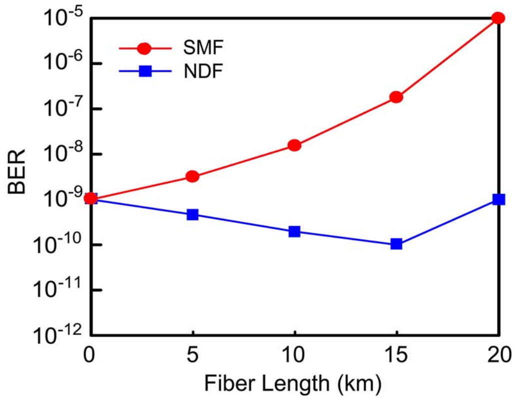

Fig. 6. Measured BER value as a function of fiber length.

chirp is to introduce a negative chirp parameter into (3) and (4). After employing NDF as the transmission medium, (3) and (4) can be changed as:

$$\frac{\mathrm{HD}_2}{\mathrm{C}} = \frac{1}{4} m\ddot{\beta} L\Omega \sqrt{(4 \cdot (\Delta \upsilon + \beta_{\mathrm{NDF}}))^2 + (\ddot{\beta} L \Omega^3)^2} \tag{5}$$

$$\frac{\mathrm{IMD}_3}{\mathrm{C}} = -\frac{9}{32} (m\ddot{\beta} L\Omega)^2 \left[4 \cdot (\Delta \upsilon + \beta_{\mathrm{NDF}})^2 + \Omega^2\right] \tag{6}$$

where β_{NDF} is the negative dispersion parameter attributed to NDF. The equations show that the lowest HD_2/C and $\mathrm{IMD}_3/\mathrm{C}$ values can be achieved as $(\Delta \upsilon + \beta_{\mathrm{NDF}})^2$ reaches the lowest value. The measured BER value as a function of fiber length are presented in Fig. 6. The effect of the accumulated negative dispersion results in the apparent improvement in BER performance as NDF length is increased up to 15 km. The positive chirp of VCSEL is compressed by the negative dispersion of NDF, thereby resulting in an improvement in transmission performance. Nevertheless, BER performance is degraded when NDF length exceeds 15 km. A large amount of negative dispersion results in an over compensation and degrades the transmission performance of systems. However, when the NDF length reaches 20 km, the measured BER value is approximately 10^{-9}. This value still meets the high-quality PON performance demand ($\leq 10^9$). To clarify the improvement achieved with the proposed set-up, a comparison with a two-way PON employing single-mode fiber (SMF) as the transmission medium is also presented in Fig. 6. BER performance is degraded as SMF length is increased. Such a deterioration in the result can be attributed to the accumulated positive dispersion interaction with the positive chirp of the directly modulated VCSEL.

Polarization mode dispersion (PMD) is one of the major concerns for 60-Gbps PON. In fiber, pulse broadening can be estimated from the time delay ΔT between the two polarization components during propagation of the pulse. For a fiber of length L, ΔT is given by [12]:

$$\Delta T = L \cdot |\beta_x - \beta_y| = L \cdot \Delta\beta \tag{7}$$

where the subscripts x and y identify the two orthogonally polarized modes, and $\Delta\beta$ is related to the difference in group velocities along the two principal states of polarization. From (7), PMD obviously becomes one of the limiting factors for lightwave transmission systems designed to operate over long distances at high data rates. However, given that the NDF length is only 20 km, the BER performance degradation due to PMD is limited. Thus, a PMD compensation scheme is not required for high data rates in short-haul two-way PON.

The measured BER curves of the 60-Gbps data channel under the conditions of back-to-back (BTB), over 15-km NDF transmission, and 20-km NDF transmission scenarios are shown in Fig. 7. A power penalty of about 0.4 dB is existed between the 15-km NDF transmission and

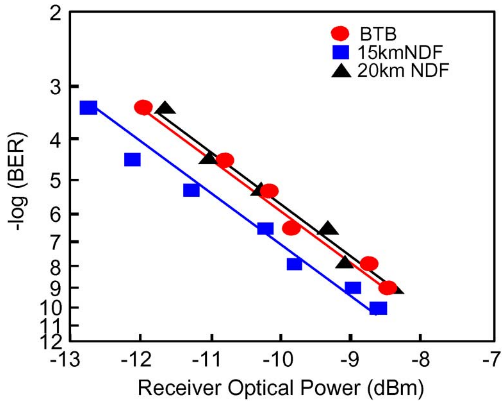

Fig. 7. Measured BER curves of the 60-Gbps data channel under the conditions of BTB, 15-km NDF transmission, and 20-km NDF transmission scenarios.

BTB scenarios at BER of 10^{-9}. Furthermore, a power penalty of around 0 dB is observed between the BTB and 20-km NDF transmission scenarios at BER of 10^{-9}. Such results can be attributed to the use of two-stage injection-locked 1.55-μm VCSELs transmitter and NDF. The use of two-stage injection-locked 1.55-μm VCSELs transmitter significantly extends the 3-dB bandwidth, resulting in systems with lower HD_2/C and IMD_3/C. HD_2/C and IMD_3/C can be stated in terms of the modulation frequency f and the gain of the laser medium $g(f)$ [13]:

$$\frac{HD_2}{C} \cong 10\log\left\{ m\frac{\left(\frac{f}{f_r}\right)^2}{g(2f)} \right\} \tag{8}$$

$$\frac{IMD_3}{C} \cong 10\log\left\{ \frac{m^2}{2}\frac{\left(\frac{f}{f_r}\right)^4 - \frac{1}{2}\left(\frac{f}{f_r}\right)^2}{g(f)g(2f)} \right\}. \tag{9}$$

From (8) and (9), both HD_2/C and IMD_3/C can obviously become very small as $f \ll f_r$. These HD_2/C and IMD_3/C reductions provide systems with better BER performance and lead to the improvement of receiver sensitivity. Moreover, the positive chirp of the directly modulated two-stage injection-locked 1.55-μm VCSELs transmitter is compressed by the negative dispersion of NDF, thereby leading to an improvement in BER performance.

Fig. 8(a)–(c) display the eye diagrams under the conditions of BTB, 15-km NDF transmission, and 20-km NDF transmission, respectively. Clear eye diagrams are obtained under these three scenarios. The amplitude and phase fluctuations in the eye diagrams are not observed when two-stage injection-locked 1.55-μm VCSELs transmitter and NDF transmission medium are employed.

As to the frequency response of the three-stage injection-locked 1.55 μm VCSELs, the frequency responses of the one-stage/two-stage/three-stage injection-locked 1.55 μm VCSEL(s) are plotted in Fig. 9. For three-stage injection-locked 1.55-μm VCSELs, the 3-dB bandwidth is increased up to 80 GHz. It means that the three-stage injection-locked 1.55-μm VCSELs transmitter is brawny enough for 80 Gbps transmission. To obtain high 3-dB bandwidth, the wavelengths of the injected lights should be carefully chosen to obtain the optimal enhancement in the frequency response of the three-stage injection-locked VCSELs. For the first-stage injection locking, the wavelength of the master laser (DFB LD) should be slightly longer than that of the slave laser (VCSEL1) to obtain a flat frequency response; that is, positive wavelength detuning should be employed to obtain the first-stage injection locking. For the second-stage injection locking, the wavelength of the master laser (one-stage injection-locked VCSEL1) should be slightly shorter than that of the slave laser (VCSEL2) to obtain a high-frequency resonance

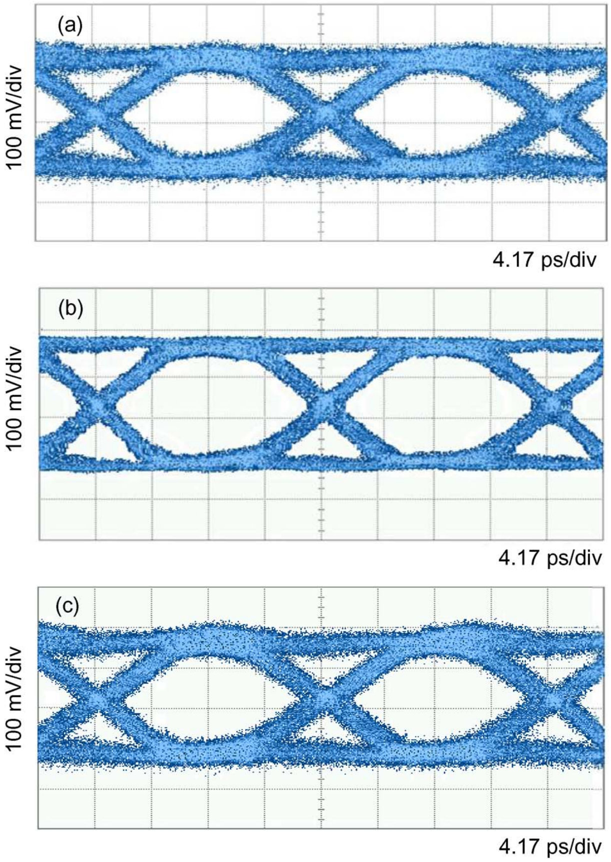

Fig. 8. Eye diagrams under the conditions of (a) BTB, (b) 15-km NDF transmission, and (c) 20-km NDF transmission.

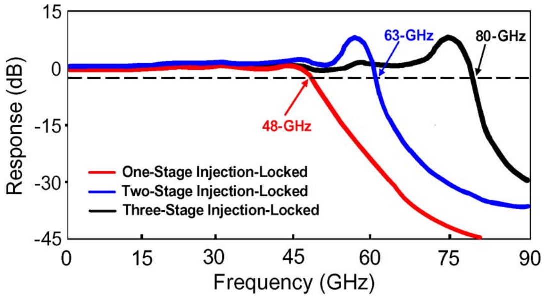

Fig. 9. Frequency responses of the one-stage/two-stage/three-stage injection-locked 1.55-μm VCSEL(s).

peak; that is, negative wavelength detuning should be employed to obtain the second-stage injection locking. For the third-stage injection locking, the wavelength of the master laser (two-stage injection-locked VCSEL2) should also be slightly shorter than that of the slave laser (VCSEL3) to obtain a high-frequency resonance peak; that is, negative wavelength detuning should be employed to obtain the third-stage injection locking.

4. Conclusion

A 20 km/60 Gbps two-way PON based on directly modulated two-stage injection-locked 1.55-μm VCSELs transmitters and NDFs is proposed and demonstrated. A 60-Gbps data stream is successfully direct-modulated and delivered up to a maximum of 15 km NDF. To be the first one of employing directly modulated two-stage injection-locked 1.55-μm VCSELs transmitters and NDFs in a two-way PON, impressive BER performance and clear eye diagrams are obtained over a 20-km NDF transport. Such two-stage injection-locked 1.55-μm VCSELs transmitters and NDFs-based two-way PON are promising options and attractive features that could accelerate PON deployment.

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