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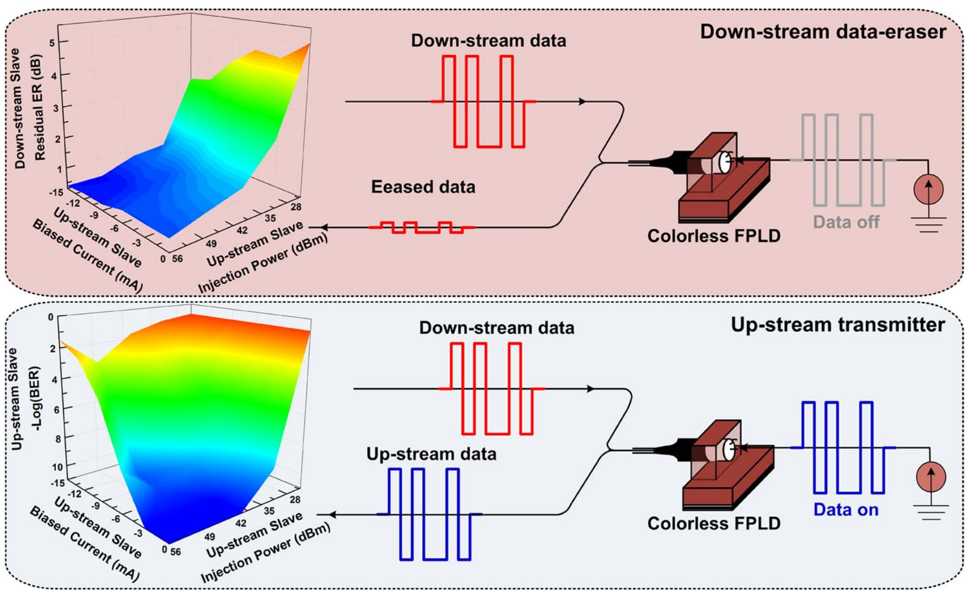

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Data Erasing and Rewriting Capabilities of a Colorless FPLD Based Carrier-Reusing Transmitter

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Abstract: The inherent data-erasing functionality of a 10-Gb/s colorless Fabry–Pérot laser diode (FPLD) wavelength controlled by reusing a downstream optical carrier with encoded data is explored. By operating the injection-locked colorless FPLD at high dc bias, the unique *in situ* data-erasing mechanism is attributed to the almost identical power-to-current slope, regardless of optical injection-locking level. When reusing the downstream carrier, the injection-locked upstream colorless FPLD can significantly suppress the extinction ratio of the residual 10-Gb/s downstream data from 7.1 to $<$ 1 dB. This facilitates direct reuse of the downstream carrier without the need for an additional data eraser. With the data-erasing capability under 0-dBm injection, the carrier-reused upstream transmission successfully delivers on–off keying data up to 10 Gb/s with a signal-to-noise ratio of 6.2 dB and an extinction ratio of 5.4 dB. Even with a downstream injection power value of only -9 dBm, the upstream bit error rate (BER) of such a dual functional colorless FPLD biased at $\geq 2I_{th}$ indicates a BER of $< 1 \times 10^{-10}$. This releases the typical demand on high power budget requested for downstream data transmission and carrier reusing. The large parametric tolerances of such a data-erasable and carrier-reusable colorless FPLD transmitter also facilitate its practical application in dense-wavelength-division multiplexed passive optical networks.

Index Terms: Carrier reusing, data erasing, injection locking, long cavity, weak resonance, colorless, Fabry–Pérot laser diode, dense-wavelength-division multiplexed passive optical network (DWDM-PON).

1. Introduction

The dense-wavelength division multiplexed passive optical networks (DWDM-PONs) with versatile transmitter architectures have emerged [1]–[8]. To solve the wavelength selection problem between down- and up-stream carriers and to reduce the system cost, several kinds of novel carrier-reusing schemes have been proposed recently [9]–[13]. Among these demonstrations, the most typical solution is the use of bidirectionally different modulation formats to avoid the crosstalk when injecting the data-encoded down-stream carrier into the up-stream transmitter [9]–[11]. Nevertheless, this inevitably raises the equipment cost since the typical carrier-reusing scheme requires additional modulators and receivers for transmitting two modulation formats.

Besides, the colorless laser diode is also developed as an universal transmitter for multiple channels in the DWDM-PON, which effectively solves the wavelength selection problem originated from typical single-mode laser diode transmitters (to fit the wavelengths for different channels). However, this raises another problem on the requirement of master sources for remotely controlling the carrier wavelength of the colorless laser diode. The most simplified and cost-effective approach is to employ the down-stream carrier reusing technique. Another possibility is directly reusing the data-encoded down-stream carrier to injection-lock the up-stream transmitter after down-stream data erasing [14]–[23]. However, all of the presented schemes still suffer from the need for additional data erasers.

By using a gain-saturated semiconductor optical amplifier (SOA) to erase the down-stream data [14]–[17], the crosstalk can be greatly reduced as the residual down-stream data seeded into the up-stream transmitter is minimized. This facilitates the use of non-return-to-zero on-off keying (NRZ-OOK) format in directly modulated up- and down-stream transmitters [18], [19] for simplifying the system architecture. To further reduce the crosstalk, a self-feedback loop was proposed by increasing the continuous-wave power level in SOA so as to greatly compress the dynamic range and clip the amplitude of the residual down-stream data [14]. But the inherent intensity noise of the SOA added into the injection-locked transmitter still degrades the transmission performance. Moreover, the additional data-erasing function can be incorporated into the carrier-reusing scheme by simply using the gain-saturated reflective semiconductor optical amplifier (RSOA) as an up-stream transmitter [20]–[22]. Even through, the RSOA with limited modulation bandwidth cannot provide high-speed transmission up to now. If the relief on the additive intensity noise and the limited bandwidth of transmitters can be approached, the carrier-reusing wavelength-injection-locked transmitter will be very promising for next-generation DWDM-PON.

As expected, a low noise carrier-reusing scheme was subsequently proposed by injection-locking the typical Fabry-Pérot laser diode (FPLD) [23], [24], but it only provides a 2.5-Gbit/s up-stream transmission [25]. Although the highest data rate of up to 10 Gbit/s has recently achieved via the use of long-cavity colorless FPLDs [26], whether the data-erasing of down-stream carrier can be directly performed inside an injection-locked laser transmitter or not has never been discussed. Besides, the typical FPLD usually requires higher down-stream power than the RSOA and the colorless FPLD when performing the injection-locking [27]–[30] because its higher front-facet reflectance induces stronger cavity resonance, which inevitably enlarges the down-stream power budget requirement. Especially when performing high-speed transmission, the receiving part also requests sufficient power to achieve error-free transmission; hence, the down-stream power budget set for typical FPLDs will be insufficiently high to provide both the up-stream injection-locking and the down-stream data receiving functions concurrently. Therefore, an ideal carrier-reusing scheme for the universal transmitters with low equipment cost to fulfill the demand of low-power budget and high-speed transmission in next generation DWDM-PON at a data rate of up to 10 Gbit/s is difficult to be realized.

In this work, for the first time, the mechanism of in-situ data-suppression in the up-stream colorless FPLD injection-locked by directly reusing the down-stream on-off-keying data encoded optical carrier is experimentally demonstrated and discussed. Without the need of additional data-eraser, the up-stream colorless FPLD can directly suppress the residual data encoded on the down-stream carrier and can reuse it as an injection-locking master for up-stream transmission. That is, the up-stream colorless FPLD performs dual functionalities, including the down-stream low-noise data-eraser and the up-stream carrier-reused transmitter.

2. Experimental Setup

The testing bench for down-stream data-erasing and carrier-reusing functionalities in the colorless FPLD based up-stream transmitter is illustrated in Fig. 1. At optical line terminal (OLT), a single-mode and wavelength-tunable laser source (TLS) is employed as the reference master to deliver the optical carrier with down-stream data. A colorless FPLD with a cavity length of

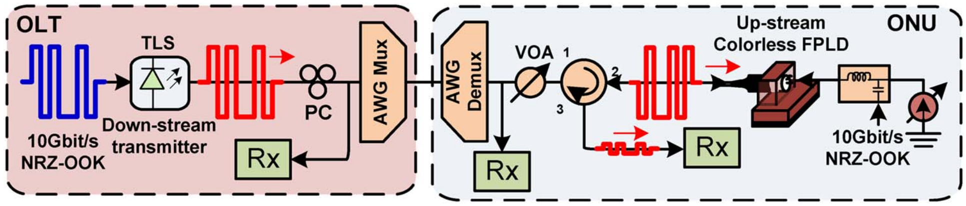

Fig. 1. Carrier-reused DWDM test system with the directly modulated TLS master for down-stream transmission and the injection-locked colorless FPLD for up-stream transmission.

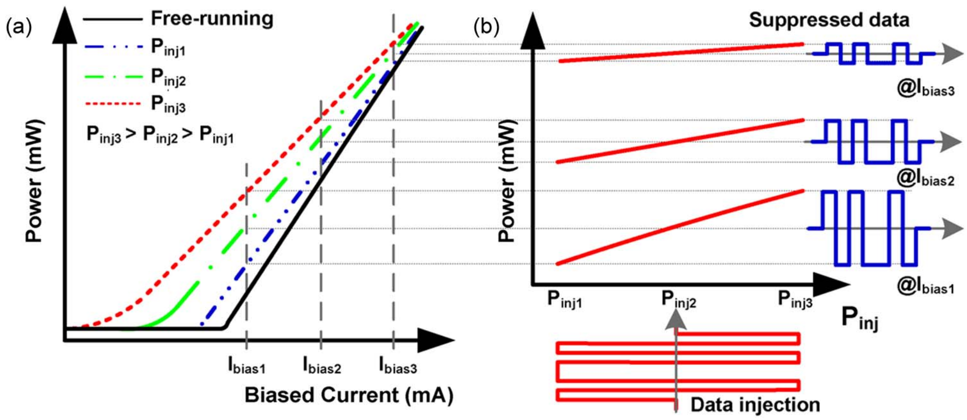

Fig. 2. (a) Schematic power-to-current response of the injection-locked colorless FPLD at different injection powers. (b) Power-to-power transfer response of the injection-locked colorless FPLD.

750 μm and a front-facet reflectance of 0.2% was employed as the down-stream data-eraser and the up-stream transmitter simultaneously. The lower front-facet reflectance leads to weaker cavity effect, which benefits from the wider injection-locking range and lower injection power requirement. To enhance the external quantum efficiency, the colorless FPLD was temperature controlled at 20 °C. To concurrently meet the demands of data-erasing and carrier-reusing, the dual functional colorless FPLD was biased from 24 to 56 mA (corresponding to 1.1$\sim$2.5 times of its threshold current) for optimization. To perform the down-stream data-erasing and the carrier-reused up-stream transmission analysis, the electrical NRZ-OOK data with a pattern length of $2^{23} - 1$ at 10 Gbit/s was encoded onto the colorless FPLD through a bias tee. The down-stream injection power was detuned from -15 to 0 dBm with a variable optical attenuator. Even though the colorless FPLD exhibits broad wavelength locking range and large polarization tolerance for external injection, the injection efficiency is maximized via the adjustment on wavelength and polarization.

To characterize the data-erasing ability, the residual data carried on the down-stream carrier before and after erasing was analyzed by a digital sampling oscilloscope (Agilent, 86100A +86106A). After down-stream carrier-reusing to injection-lock the colorless FPLD for up-stream transmission, the 10-Gbit/s NRZ-OOK up-stream data received by a standard NRZ receiver (Agilent, 83434A) was analyzed by a commercial bit-error-rate (BER) detector (Agilent, 70843A). To avoid the fluctuation of temperature affects the stability of injection-locking, a specific cooper mount was designed for the conventional TO-56-can packaged WRC-FPLD, as shown in Fig. 2. Such a mount was made by copper owing to its characteristic of high thermal conductivity. To further avoid the cooper mount affects the laser frequency response, the WRC-FPLD was insulated from touching the copper. Finally, the thermistor and the thermoelectric cooler were controlled by a modular laser diode controller (ILX Lightwave, LDC-3900) to maintain the temperature of the WRC-FPLD at 23.5 °C.

3. Results and Discussions

When reusing the data-encoded down-stream carrier for injection-locking, the injection-locked colorless FPLD is concurrently employed as the down-stream data eraser and the up-stream data transmitter. To discuss the unique data-erasing mechanism, a schematic power-to-current response of the injection-locked up-stream colorless FPLD with different injection-locking powers is shown in Fig. 2(a). The incoming optical OOK data does not make the injection-locked colorless FPLD distinctly switching its power-to-current response, thus confining the power switching within a finite range and suppressing the down-stream data. This effectively prevents the up-stream modulation from the crosstalk with the residual down-stream data in the injection-locked colorless FPLD. In particular, due to the inherent mode competition at a highly biased condition, the power-to-current response of the injection-locked colorless FPLD almost approaches that at free-running case, which further helps to completely erase the down-stream data. This facilitates the clipping of any fluctuation on the injected carrier. Therefore, the up-stream colorless FPLD can also be used to suppress the optical data encoded on carrier. By transforming the x-axis of Fig. 2(a) from the current to the injection power, the power-to-power transfer response of the injection-locked up-stream colorless FPLD is schematically illustrated in Fig. 2(b). The optical NRZ-OOK data encoded on the injected continues-wave carrier shrinks its peak-to-peak amplitude owing to the nearly unchanged quantum efficiency of the injection-locked up-stream colorless FPLD. It leads to the inertial power-to-current response with confined output amplitude under different injection-locking conditions, and all of the P-I responses will eventually approximate to that of free-running condition at highly biased current. The almost identical dP_{out}/dI results in the decreased slope of power-to-power transfer response $(dP_{\text{inj}}/dP_{\text{out}})$ at high bias, indicating that the injected data can be further suppressed by simply increasing the biased current of the up-stream colorless FPLD.

The simulated frequency responses of the WRC-FPLD under injection-locking are shown in Fig. 4. By increasing the injection-locking power, the modulation bandwidth and the throughput intensity of the injection-locked WRC-FPLD can be improved. In addition, the relaxation oscillation frequency of the injection-locked WRC-FPLD can be slightly enhanced due to the enhancement on both the relative strength of the coupling and gain coefficients. However, as the injection power goes to 6 dBm or 9 dBm, such a high injection power level degrades the throughput response instead of improving the modulation bandwidth. The over-injected and unmodulated photons are unable to create more stimulated emission photons but being noise component in the slave laser cavity. Nevertheless, the critical value of injection power is dependent on many parameters, such as the front-facet reflectance, the cavity length, etc. According to our simulation results, the critical value of injection power increases as the front-facet reflectance is enlarged because of the enhanced cavity effect. The WRC-FPLD with larger front-facet reflectance possesses smaller damping coefficient, thus requiring higher injection level to stabilize the single-mode output performance.

The working principle of dual functional colorless FPLD based down-stream data-eraser and up-stream data transmitter is illustrated in Fig. 3(a). The up-stream colorless FPLD can serve as both a data-eraser and a data transmitter via its inherent data-suppression effect under injection-locking, which greatly reduces the amplified spontaneous emission (ASE) noise when comparing with the similar data-eraser by using the gain-saturated RSOA. In the proposed DWDM-PON, the up-stream colorless FPLD can directly reuse the down-stream data encoded optical carrier for injection-locking and can be directly modulated to transmit the up-stream data simultaneously, as also shown in Fig. 3(a). Owing to the low-noise property, the colorless FPLD based up-stream transmitter is very compact for realizing the high-speed carrier-reused DWDM-PON.

The completely coherent TLS reference master is used to carry the down-stream data and to injection-lock the up-stream colorless FPLD, as shown in the top of Fig. 3(b). Originally, the free-running up-stream colorless FPLD shows a broadband gain spectrum expanded from 1562 to 1595 nm with dense longitudinal modes spaced by 0.5 nm, which is due to its low front-facet reflectance of less than 1.2% and long cavity length of 750 μm [see the middle row of Fig. 3(b)].

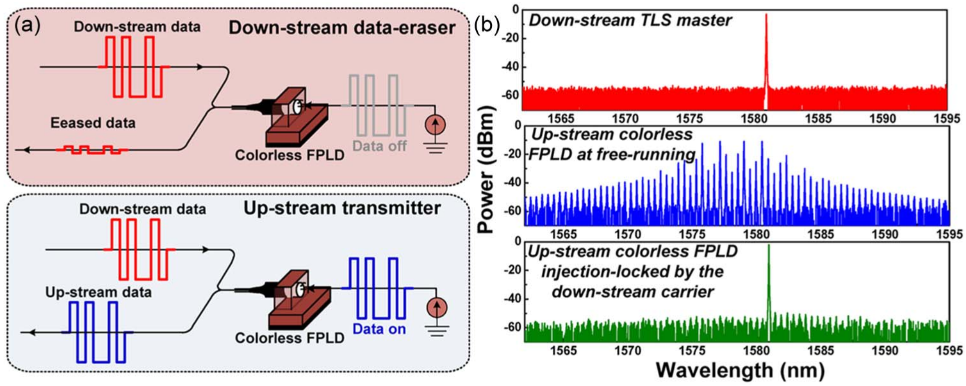

Fig. 3. (a) Schematic diagrams of dual functional colorless FPLD based down-stream data-eraser and up-stream data transmitter. (b) Spectra of the down-stream TLS master (upper), up-stream slave colorless FPLD under free-running (middle), and injection-locking with the TLS master (lower).

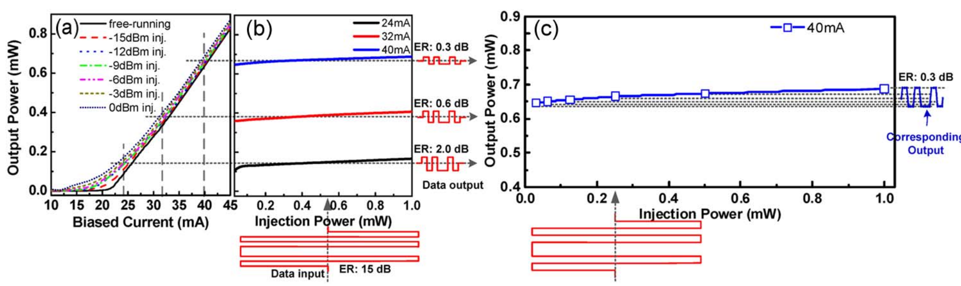

Fig. 4. (a) Power-to-current response of the injection-locked up-stream colorless FPLD at different injection powers. (b) Power-to-power transfer response of the injection-locked up-stream colorless FPLD. (c) Zoom-in power-to-power transfer response of the injection-locked up-stream colorless FPLD biased at 40 mA with the injected data and its corresponded output.

The laser diode exhibits a locking range allowing the wavelength difference between master and slave laser diodes under injection-locking. From literatures, the optimized injection-locking wavelength needs to be slightly red-shifted as compared to the wavelength of the selected mode [31]. To facilitate the injection-locking, the wavelength of single-mode down-stream carrier is slightly red-shifted by 0.15 nm with respect to the selected longitudinal mode of the up-stream one. The up-stream colorless FPLD injection-locked by the down-stream TLS carrier can effectively approach the single-mode operation with a side-mode suppression ratio (SMSR) of 48 dB, as shown in the bottom of Fig. 3(b). Later on, the Fig. 4(a) shows the measured power-to-current responses of the injection-locked up-stream slave colorless FPLD at different down-stream injection powers. After injection-locking, the externally injected photons enhance the stimulated emission of one desired mode to help the gain competition of the up-stream colorless FPLD, which leads to a decrement of threshold current and an increment of output power. By increasing the injection power from -15 to 0 dBm, the threshold current of the up-stream colorless FPLD effectively decreases from 18 mA to 12.5 mA. However, the 15-dB increment on injection power only increases the output power of the injection-locked up-stream colorless FPLD from 0.11 to 0.17 mW with corresponding suppression on extinction ratio (ER) from 15 to 2 dB at a biased current of 24 mA.

By simply transforming the x-axis of Fig. 4(a) from the biased current to the injection power, the measured power-to-power transfer response of the injection-locked colorless FPLD shows that the input NRZ-OOK data with an original ER of 15 dB can be dramatically suppressed to less than 2 dB at biased current of higher than 24 mA, as shown in Fig. 4(b). When biasing the up-stream colorless FPLD at higher current, the inherent lasing property of the colorless FPLD

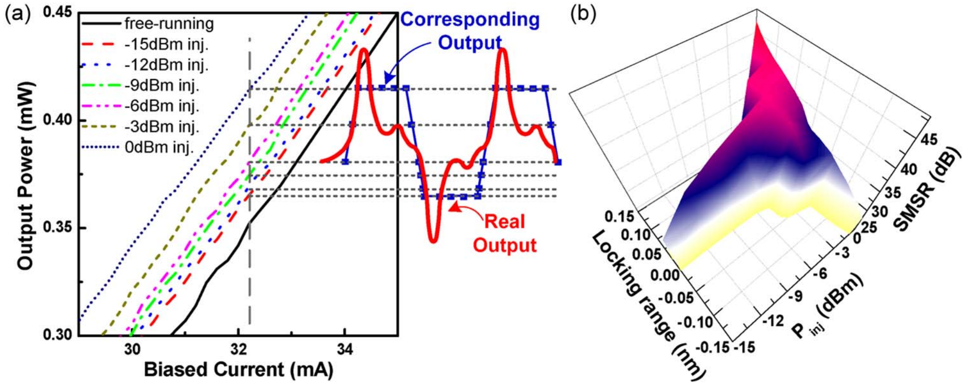

Fig. 5. (a) Illustrated diagram of the down-stream TLS reference master delivered data distortedly suppressed in the injection-locked up-stream colorless FPLD. (b) Wavelength locking range of the injection-locked colorless FPLD as a function of injection power ($P_{\rm inj}$).

becomes more dominated, and the output power is thus less sensitive to the externally injected photons. This eventually results in a decreased throughput slope of the power-to-power transfer response. Therefore, the residual ER of the down-stream data further decreases to 0.3 dB with enlarging the bias to 40 mA due to the enhanced data-erasing effect in the up-stream colorless FPLD, and its corresponding output is shown in Fig. 4(c). The colorless FPLD served as both a data-eraser and a data transmitter via its inherent data-suppression effect under injection-locking greatly reduces its ASE noise when comparing with the data-eraser by using gain-saturated SOA [32]–[35], which could be used to realize the 10-Gbit/s carrier reused DWDM-PON. Such a data-erasing mechanism in the injection-locked up-stream colorless FPLD is entirely different from the data-erasing by amplitude bleaching or clipping occurred in the gain-saturated SOA and RSOA. The data carried on down-stream carrier injecting into the up-stream colorless FPLD will induce a transient shift on its power-to-current response, and the up-stream colorless FPLD cannot completely respond the waveform of original down-stream data at such a high data rate of 10 Gbit/s. Therefore, the injected down-stream data also shows a suppressed and distorted waveform with greatly enlarged residual ER, as shown in Fig. 5(a). As the suppressed down-stream data is seriously distorted, the residual ER is calculated by the ratio $P_{\rm top}/P_{\rm base}$ to define the data-suppression capability of the up-stream colorless FPLD in the following discussion.

The wavelength locking range of the injection-locked up-stream colorless FPLD biased at 48 mA is shown in Fig. 5(b). When the injection wavelength is up-shifted away from the selected mode by 0.15 nm, a highest side-mode suppression ratio (SMSR) of 46.4 dB for the injection-locked up-stream colorless FPLD at an injection power of 0 dBm is observed. With SMSR > 30 dB, the total locking range is decreased from 0.27 nm to 0.02 nm by reducing the injection power from 0 to -15 dBm. Note that even the colorless FPLD exhibits a broader locking range than the conventional FPLD, the carried data with its bandwidth out of the locking range can be effectively suppressed, as the injection-locking mechanism of the colorless FPLD cannot follow up the modulated signal beyond locking range. This explains why the data carried by the optical carrier can be erased by injection-locking process. For colorless FPLD, the design of long weak resonant cavity and external injection-locking are two key mechanisms to achieve 10-Gbit/s operation. The weak resonant feature achieved by reducing the front-facet reflectance makes the colorless FPLD a broadened gain spectrum with slightly reduced coherence. The degraded coherence can somewhat be improved by lengthening the colorless FPLD for sufficient stimulated emitting photons at a cost of enlarged threshold current. The highly coherent injection-locked colorless FPLD up-shifts its relaxation oscillation frequency by two-three times but declines its modulation throughput intensity at low frequency region, as shown in Fig. 6(a). Under free-running operation, the colorless FPLD exhibits a relaxation oscillation frequency

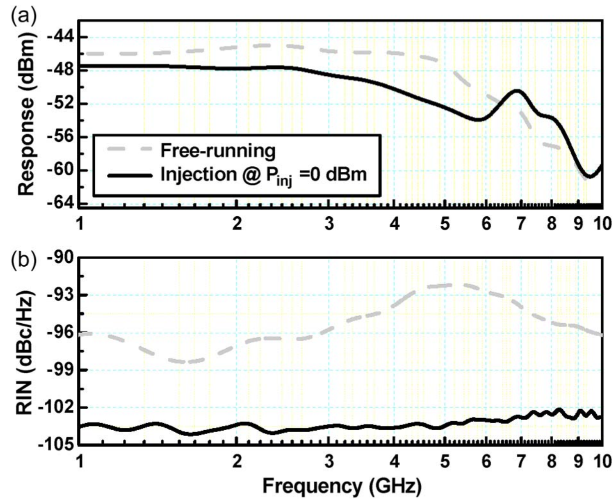

Fig. 6. (a) Frequency response and (b) RIN of the up-stream colorless FPLD at free-running and injection conditions.

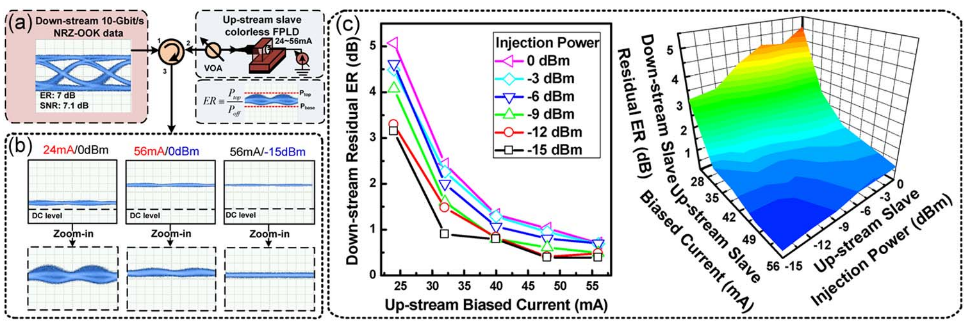

Fig. 7. (a) Eye diagrams of the 10-Gbit/s NRZ-OOK data carried by the down-stream TLS reference master. (b) Eye-diagrams and (c) 2-/3-dimensional residual ER of the down-stream 10-Gbit/s NRZ-OOK data in the up-stream colorless FPLD injection-locked by reusing the down-stream carrier.

related relative intensity noise (RIN) peak of 5.4 GHz, as shown in Fig. 6(b). After injection-locking, the colorless FPLD with enhanced coherence not only suppresses its RIN level but also up-shifts its RIN peak. The allowable modulation bandwidth of 7 GHz for 10-Gbit/s on-off-keying operation can be obtained with up-shifted relaxation oscillation frequency and maintained throughput intensity.

The highly coherent TLS reference master with a perfect 10-Gbit/s NRZ-OOK data-stream is used both for down-stream data transmission at the receiving end and for injection-locking the colorless FPLD at the up-stream end, as shown in Fig. 7(a). To experimentally verify the ability of data-erasing, the residual ER of the down-stream 10-Gbit/s NRZ-OOK data encoded on carrier is the key parameter to be evaluated. When injection-locking the up-stream colorless FPLD by reusing the down-stream carrier, the residual ER of down-stream data has to be minimized via the adjustment on operating conditions of the up-stream colorless FPLD. In the up-stream colorless FPLD transmitter, the down-stream data can be erased by setting sufficiently high DC bias, and the residual down-stream data will be regarded as the intensity noise for up-stream transmission. To further reduce the crosstalk between the residual down-stream data and the up-stream data, the eye-diagrams and the residual ER of the down-stream data erased in the up-stream colorless FPLD at different biases and injection powers are investigated, as shown in Fig. 7(b) and (c). At same injection power of 0 dBm, increasing the biased current from 24 to 56 mA for the injection-locked up-stream colorless FPLD dramatically suppresses the

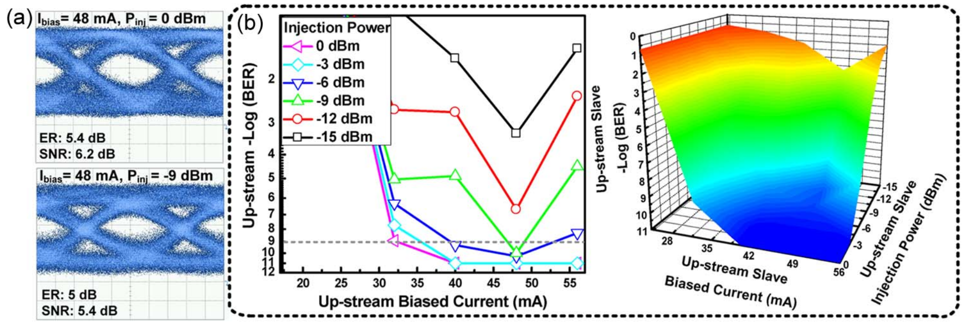

Fig. 8. (a) Eye-diagrams of 10-Gbit/s NRZ-OOK data delivered by the up-stream colorless FPLD biased at 48 mA with injection powers of 0 dBm (left) and −9 dBm (right). (b) 2-/3-dimensional BER of the 10-Gbit/s NRZ-OOK data delivered by the up-stream colorless FPLD injection-locked by the data-encoded TLS reference master.

residual ER of the down-stream data from 5 to 0.7 dB, as shown in Fig. 7(b). Moreover, the residual ER can be further reduced to less than 0.4 dB by decreasing the down-stream injection power to −15 dBm. Because the inherent mode competition dominates the transient behavior of the injection-locked up-stream colorless FPLD, which eventually minimizes the corresponding shift of the power-to-current transfer function at lasing condition to confine the power switching range. The residual ER of the suppressed down-stream data slightly increases at low biased current due to the slightly increased intensity noise by the incompletely erased down-stream data under weak data-suppression effect. Fortunately, by increasing the biased current of the up-stream colorless FPLD to higher than 32 mA, the residual ER of the down-stream data delivered by the TLS reference master is greatly reduced from 5 dB to $<$ 1 dB. As a result, the up-stream colorless FPLD operated at high bias can further enhance its data-erasing effect without the need of decreasing the injection power, because the insufficient injection power may degrade the up-stream transmission performance.

At same injection power level, the highly biased up-stream colorless FPLD can enhance the data-erasing effect and provide large modulation bandwidth for up-stream transmission; however, the inherent mode competition is also enhanced to reduce the SMSR. Therefore, the back-to-back BER of the data delivered by the up-stream colorless FPLD at different biases and injection powers is analyzed, as shown in Fig. 8. Apparently, the insufficient biased current cannot provide the injection-locked up-stream colorless FPLD an extended modulation bandwidth with a suppressed RIN to improve its transmission performance. On the contrary, the overly biased colorless FPLD causes strong mode competition to result in high MPN and low SMSR and to degrade the up-stream data quality. Thus, the lowest BER valley occurs when the up-stream colorless FPLD is strategically biased at 48 mA. The BER also reveals that increasing the injection power of the up-stream colorless FPLD can greatly improve the BER performance due to the increased SMSR. When reusing the data encoded down-stream carrier for injection-locking, the injection-locked up-stream colorless FPLD biased at 48 mA successfully delivers a 10-Gbit/s NRZ-OOK data with the highest SNR of 6.2 dB and ER of 5.4 dB at an injection power of 0 dBm, as shown in the left of Fig. 8(a). The injection power provided by the down-stream TLS reference master inevitably suffers from the insertion losses of passive components (e.g., the 25-km fiber and the arrayed waveguide grating based Mux/DeMux), and then must be divided by an optical coupler for serving the carrier reusing and the data receiving in the practical carrier-reused DWDM-PON system. Hence, the up-stream colorless FPLD with less required injection power is more favorable when considering the down-stream power budget. Although increasing the down-stream injection power helps to suppress the RIN and MPN for improving the up-stream transmission performance, it is not practical under the consideration on the power budget of system. Due to the high injection efficiency of the colorless FPLD, the decrement on the injection power by 9 dB only causes an SNR degradation by 0.8 dB on up-stream data, as shown in the bottom of Fig. 8(a).

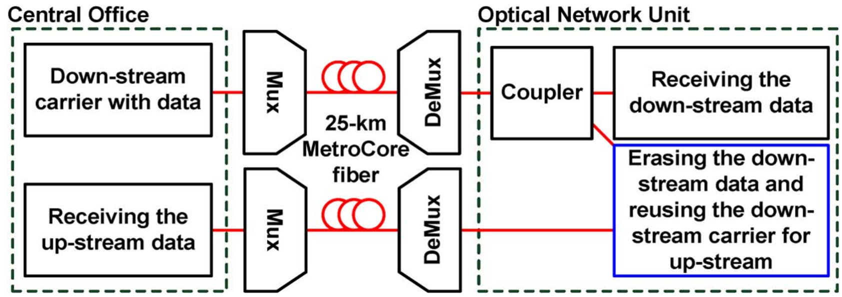

Fig. 9. Schematic diagram of the down-stream carrier reused full-duplex DWDM-PON system.

The NRZ data delivered by the up-stream colorless FPLD biased at 48 mA can achieve the lowest BER of lower than 10^{-10} with required down-stream injection power as low as -9 dBm. Typically, without the use of FEC, the BER of 10^{-9} is considered to represent the error-free transmission for telecommunications [36] and is more common than that of 10^{-12} for datacom applications in fiber-optic communication [37]. In our case, the received power sensitivity required for BER of less than 10^{-10} is particularly set to guarantee the telecommunication performance. To meet the acceptable BER of 10^{-9} for telecommunication transmission, a required down-stream injection power as low as -9 dBm is enough for the injection-locked colorless FPLD biased at 48 mA to deliver the up-stream data. In the meantime, the residual ER of the down-stream data after erasing is also suppressed to 0.6 dB, which confirms the dual-functionalities of the injection-locked up-stream colorless FPLD. For up-stream injection-locked colorless FPLD with a threshold current of 22.4 mA, the biased current of 48 mA means that the modulating current (I_{pp}) needs to be increased to 51.2 mA for achieving the highest data on/off extinction ratio. It means that the driving voltage (V_{pp}) of 2.56 V is needed when considering the 50-ohm impedance matching circuit, which is lower than that of 5 V delivered from a driver IC for intensity modulation.

In this work, we only employ the residual down-stream ER as a criterion to describe the qualified down-stream carrier for reusing as the injection master. However, the up-stream ER is not a dominated factor to affect the transmission performance. Typically, the up-stream on/off ER data is a less important parameter than the SNR to affect the transmission performance since the BER can be calculated by $\mathrm{BER} = 0.5 \cdot erfc\{[(\mathrm{ER}-1)/(\mathrm{ER}+1)] \cdot (\mathrm{M} \cdot \mathrm{SNR}/2)^{0.5}\}$ with M denoting the receiver gain. Thus, for the up-stream data delivered from the up-stream colorless FPLD injection-locked by reusing the data-encoded down-stream carrier, the discussion for the effect of the down-stream ER on the up-stream BER is more straightforward than characterizing the up-stream ER. With the residual down-stream ER of less than 1 dB, the up-stream BER can meet the error-free operation when enlarging the injection level to -9 dBm at least. The higher the injecting power of reused down-stream carrier, the broader the biased tolerance of the up-stream colorless FPLD. Moreover, the residual ER of down-stream reused carrier and the ER of up-stream transmitted data are two individual parameters controlled by different operating parameters. For chirp reduction and RIN suppression, all kinds of laser diodes must be operated at high biases. The increasing modulating current is thus required to enlarge the transmitted ER; however, this is not a serious concern as most of the laser diode driver IC can easily deliver large modulating current nowadays.

To avoid the back Rayleigh scattering effect induced crosstalk between down- and up-stream data to degrade their transmission performances, we further perform the dull-duplex DWDM-PON, as shown in Fig. 9. By using two 25-km Corning MetroCore fiber rolls with a dispersion coefficient of -4 ps/nm/km at 1580 nm, the BER versus received power curves of the down- and up-stream data after back-to-back and 25-km transmissions are measured, as shown in Fig. 10. At a telecommunication standard required BER of 10^{-9}, a received power sensitivity of -16.7 dBm is observed for the down-stream back-to-back transmitted 10-Gbit/s NRZ-OOK data.

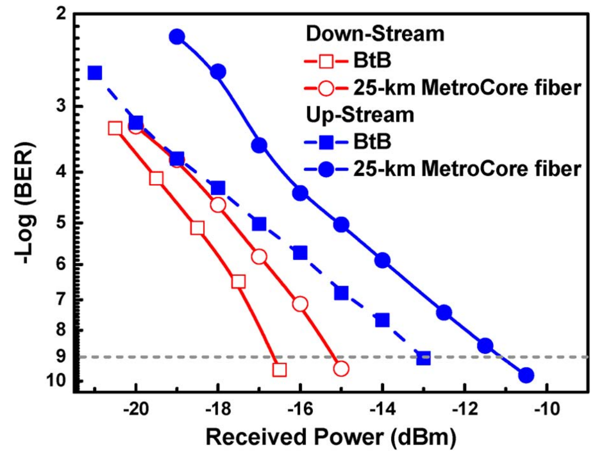

Fig. 10. Transmitted BER performance of the down- and up-stream 10-Gbit/s NRZ-OOK data.

After transmitting in MetroCore fiber over 25 km, the received power sensitivity is slightly increased to −15.2 dBm with a power penalty of only 1.5 dB at a BER of 10^{-9}. By directly reusing the down-stream data-encoded carrier to injection-lock the colorless FPLD for up-stream transmission, the up-stream transmitted 10-Gbit/s NRZ-OOK data can also achieve error-free criterion after back-to-back and 25-km transmissions at received power sensitivities of −13 and −11.5 dBm, respectively. According to the response of BER versus received power, a power budget of 17 dB is requested for the proposed carrier reusing DWDM-PON system. In detail, the down-stream transmitter delivers an average power of 2 dBm. After determining the insertion loss of about −10 dB for the full-duplex DWDM-PON system (including multiplexer, de-multiplexer and 25-km MetroCore fiber), the down-stream carrier with encoded data still remains an average power of −8 dBm for both receiving and injection-locking at the ONU. When considering the least powers of −15 dBm required for down-stream receiving and −9 dBm required for injection, an 80:20 optical coupler is employed, which divides 20% (−7 dB loss) power to receiving branch and 70% (−1 dB loss) power to injection-locking branch. Therefore, a power budget of at least 17 dB is needed for the down-stream carrier reused full-duplex DWDM-PON. Typically, the down-stream data eraser is located before the up-stream transmitter (or modulator) in a down-stream carrier reused DWDM-PON, which bleaches the down-stream data before carrier reusing. To remove the data eraser used in a down-stream reused DWDM-PON by using a colorless FPLD with combined functions (data erasing and carrier reusing), our proposal is to use only one colorless laser diode up-stream transmitter that can in-situ perform the functions of down-stream data erasing and carrier reused up-stream transmission simultaneously. This design greatly simplifies the network architecture. To suppress the additive intensity noise and to release the limited modulation bandwidth compromised with the broadband colorless operation, the direct reuse of a data-encoded down-stream carrier in a colorless FPLD transmitter with inherent data-erasing function is proposed for the first time.

4. Conclusion

The dual functional colorless FPLD with down-stream, data-erasing, and carrier-reusing capabilities is demonstrated for the first time, which plays the roles of not only the up-stream slave transmitter at 10 Gbit/s but the *in-situ* data-eraser for reusing the data-encoded down-stream carrier as well. Such a new class of carrier-reusing transmitter with its inherent data-suppression effect under injection-locking at high DC bias is unique, which greatly suppresses the residual ER of data carried by the highly coherent TLS reference master. It helps to reduce the crosstalk between the injected down-stream data and the encoded up-stream data in the colorless FPLD when realizing the carrier-reused transmission. The residual ER of the down-stream data can be suppressed from 7 dB to < 1 dB by simply increasing the DC bias of the up-stream colorless

FPLD to higher than twice the threshold current. The carrier-reused up-stream colorless FPLD biased at 48 mA successfully delivers a 10-Gbit/s NRZ-OOK data with an SNR of 6.2 dB and ER of 5.4 dB at an injection power of 0 dBm. Even with a punishment on the injection power by 9 dB, the SNR of the up-stream data degraded by only 0.8 dB is observed. The up-stream BER indicates that the up-stream colorless FPLD biased at 48 mA can effectively compromise the down-stream ER suppression and the up-stream SMSR-enhancement to achieve the lowest BER of $< 1 \times 10^{-10}$ with a required down-stream injection power as low as -9 dBm. With such *in-situ* low-noise data-erasing and carrier-reusing capabilities, the cost-effective colorless FPLD has successfully demonstrated its dual functionalities for the compact down-stream eraser and the up-stream data transmitter at 10 Gbit/s.

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