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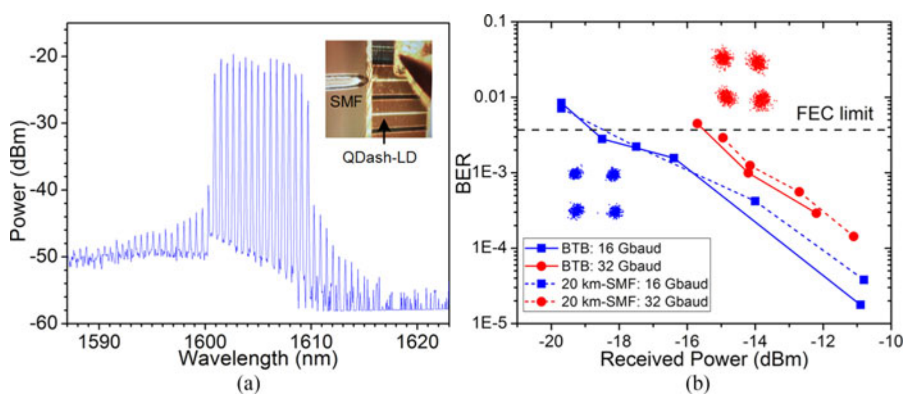

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L-Band Quantum-dash Self-Injection Locked Multiwavelength Laser Source for Future WDM Access Networks

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Abstract: We propose and demonstrate a compact, cost-effective, multiwavelength laser source employing self-injection locking scheme on InAs/InP quantum-dash (Qdash) laser diode. The device is shown to exhibit Fabry–Perot modes or subcarriers selectivity of 1 to 16 between ∼1600–1610 nm, with corresponding mode power (side mode suppression ratio) variation of ∼10 (∼38) to ∼−2.5 (∼22) dBm (dB), and able to extend beyond 1610 nm, thereby encompassing >30 optical carriers. Then, we utilized a single self-locked optical carrier at 1609.6 nm to successfully transmit 128 Gb/s dual-polarization quadrature phase shift keying signal over 20 km single mode fiber with ∼−16 dBm receiver sensitivity. To stem the viability of unifying the transceivers and addressing the requirements of next generation access networks, we propose self-seeded Qdash laser based wavelength division multiplexed passive optical network, capable of reaching a data capacity of 2.0 Tb/s ($16 \times 128\,\mathrm{Gb/s}$) in L-band.

Index Terms: InAs/InP quantum-dash lasers, multi-wavelength laser source, self-injection locking, passive optical networks.

1. Introduction

Efficient light sources play a key role in advancing future optical access networks to address the ever growing demand of high-speed broadband services by the end-users. Thanks to the significant increase in the penetration rate of last-mile-access Fiber-to-the-home (FTTH) technology with passive optical network (PON) being the workhorse of this transport system. Hereof, wavelength division multiplexed (WDM) PON (WDM-PON), exploiting the large bandwidth of optical fibers, has been identified as the next generation PON (NG-PON) infrastructure, providing Gb/s upstreaming and downstreaming data rates for the standardized 10G access network [1], with a potential to reach even higher data rates for the proposed 100G and 400G systems [2], [3]. Hence, deployment of compact, high efficiency, low power consumption, and cost effective light sources in the optical network unit (ONU) and optical line terminal (OLT) of WDM-PONs, is expected to bring incessant advancements to this transport infrastructure.

Moreover, colorless PONs based on unified wavelength independent sources, have been identified as an attractive route for attaining cost-effective and high-performance future optical access networks [2]. In this scenario, one of the best candidates for realizing such sources is a typical low-cost Fabry-Perot (FP) laser diodes assisted with injection locking scheme, compared to expensive distributive feedback (distributive Bragg reflector) DFB (DBR) lasers [4] or reflective semiconductor optical amplifiers (RSOA) counterparts. Here the subcarrier wavelength or FP mode is controlled by either an external seeding source or a passive device such as bandpass filter in case of self-seeding.

Various external-injection locked transmitter light sources have been demonstrated for NG-PONs based on WDM infrastructure and in C-band wavelength window. For instance, RSOA [5] and integrated modulator-RSOA (R-EAM-SOA) [6] exploiting wavelength reuse technique, typical Fabry-Perot laser diodes (FP-LD) [4], specific weak-resonant cavity FP-LD (WFP-LD) [7], etc., with corresponding achieved data capacity of 4×26 Gb/s, 24×10 Gb/s, 16×10 Gb/s, and 28×20 Gb/s using OOK-NRZ modulation scheme for the former three cases and 16-QAM-OFDM for the latter one. In general, wavelength tunability of these sources is in the range of 10–32 nm and fundamentally states the integration of number of subscribers in WDM-PON. This is an essential requirement of unified transceivers for mass production and deployment in flexible and scalable NG-PONs. On other front, different external seeding light sources such as amplified spontaneous emission sources [8], superluminescent diodes (SLD) [9], FP-LDs [4], WFP-LDs [10], frequency combs [11], tunable laser diodes [12] have been employed in injection locked WDM-PONs. While the former two suffer with limited power and intensity noise issues, the latter are either narrow band tunable or based on energy hungry nonlinear optics and requires bulky and complex system for generation and tuning.

Recently, a new class of inherently inhomogeneous Qdash active region based multi-wavelength laser source, exploiting mode-locking technique, have been employed as an external seeding source at 1550 nm for 16×2.5 Gb/s data capacity WDM-PON [6], [13]. Moreover, very recently, C-band mode-locked Qdash-LDs were utilized as a comb source for 4 Tb/s (23×45 Gbaud) polarization division multiplexed (PDM)-QPSK [14] and 12 Tb/s (60×20 Gbaud) PDM-32QAM [15], over 75 km single mode fiber (SMF). Exploiting the wide and tunable gain profile offered by these quantum-confined nanostructures, deployment of broadband Qdash FP laser diode (Qdash-LD) as a source in OLT and ONU have also been proposed and investigated in far L-band regime ($\sim$1620 nm) to address future 100G and 400G networks under the expanded spectrum wavelength plan [12]. In this case, 100 Gb/s dual-polarization quadrature phase shift keying (DP-QPSK) data transmission is reported utilizing external modulation scheme rather than direct modulation, owing to the maximum date rate per subcarrier limitation posed in the latter case (up to 25 Gb/s [5]) which might restrict the capacity of future NG-PONs. This exploration is expected to be the key for addressing the future WDM access requirements rather than relying only on C-band communication window and direct modulation scheme. Therefore, these demonstrations qualify broadband Qdash-LD, which exhibits wide emission controllability spanning from S- to U-bands, as a promising multi-wavelength external seeding as well as transmitter source for NG-PONs.

In this work, we further explored the features of InAs/InP Qdash-LD to propose and demonstrate a highly flexible selective multi-wavelength source based on self-injected locked scheme and emitting in mid L-band region. The device exhibits different numbers of FP modes or subscribers with selectivity from 1 to 16 ($\sim$1600–1610 nm), corresponding to mode power (side mode suppression ratio (SMSR)) variation of $\sim$10 ($\sim$38) to $\sim$–2.5 ($\sim$22) dBm (dB), by controlling the number of re-injected feedback modes into the laser via a tunable band pass filter (BPF). Furthermore, the spectral purity of the locked modes is investigated by successfully transmitting 128 Gb/s DP-QPSK

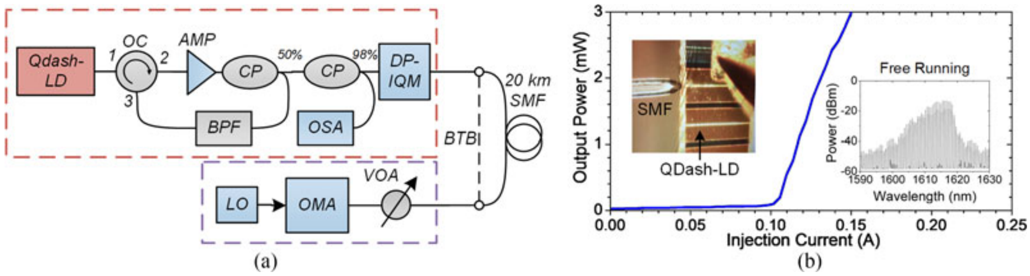

Fig. 1. (a) Experimental block diagram consisting of self-injection locking arrangement and the transmission setup for the bare Qdash-LD. (b) SMF coupler optical power and current (*L-I*) curve of Qdash-LD at heatsink temperature of 14 °C. Insets show a free running lasing spectrum at near threshold biasing current of 110 mA, measured directly at the SMF end, and an image of bare Qdash-LD coupled to a lensed SMF. OC: optical circulator, AMP: EDFA, CP: coupler, BPF: band pass filter, OSA: optical spectrum analyzer. DP-IQM: dual polarization-in phase quadrature modulator, BTB: back to back configuration, VOA: variable optical attenuator, OMA: optical modulation analyzer, LO: local oscillator.

data signal over 20 km SMF, employing a single 1609.6 nm self-seeded mode as a subcarrier and dual-polarization in-phase and quadrature external modulator (DP-IQM), with −16 dBm receiver sensitivity. Based on the accomplished results, we also propose a unified transceiver based next generation WDM-PON architecture with 2.0 Tb/s potential aggregate capacity employing this new class of self-injection locked Qdash-LD as a multi-wavelength emitter. This realization of small-foot print, cost-effective, and energy efficient transceivers in PONs further affirm the potential of this source for NG-PONs.

2. InAs/InP Quantum-Dash Laser Diode

Fig. 1(a) illustrates the complete experimental block diagram consisting of self-injection locking arrangement for Qdash-LD (left part) and the subsequent data transmission setup (right part). We utilized a broad gain profile InAs/InGaAlAs/InP Qdash-LD grown by Molecular Beam Epitaxy (MBE) on n-InP substrate. The active region composed of four layers of InAs Qdashes embedded in an asymmetric $In_{0.64}Ga_{0.16}Al_{0.2}As$ quantum-wells, and separated by five different thickness $In_{0.50}Ga_{0.32}Al_{0.18}As$ barrier layers, to promote intended dispersion in Qdash sizes and hence the ground-state energy transitions. More details about the growth and laser fabrication are given in [16]. In this work, we utilized a bare 600 μm cavity length and 3 μm ridge width as-cleaved FP laser device in continuous wave (CW) current operation with p-side up configuration, placed on a thermo-electric cooler (TEC) controlled brass base at 14 °C. The single facet power is coupled to a lensed SMF with ~5% (−13 dB) coupling efficiency via a 3-axis manual translation stage, as shown in the left inset of Fig. 1(b). The SMF optical power versus the injection current characteristics (L-I) is plotted in Fig. 1(b) showing a threshold current of ~100 mA and near threshold slope efficiency of ~0.07 W/A. A broadband lasing emission at 110 mA, incorporating multiple FP modes, is evident from the free running spectrum of the device, as depicted in the inset of Fig. 1(b), and measured directly at the end of SMF using an optical spectrum analyzer (OSA) with 0.06 nm resolution bandwidth. A total single facet coupled SMF power of ~0.5 mW (~−3 dBm) is measured, with ~1613 nm central lasing wavelength and ~8–10 nm −3 dB lasing bandwidth (i.e., ~1600–1620 nm). Considering a FP mode measured linewidth of ~0.06 nm with 0.6 nm mode spacing (cavity length dependent), the mode power within the lasing bandwidth is calculated to be ~−10 (~−23) dBm at the laser facet (SMF) end. Since, the laser is based on an un-optimized device structure, the heatsink temperature and the injection current values are regulated to maximize the overlap between the lasing spectrum and erbium doped fiber amplifier (EDFA) operating wavelength window. However, it is worth noting that both bandwidth (~50 nm) and single laser facet power (>100 mW) of the Qdash-LD could be substantially improved by employing an optimized device structure (active region in particular) and coupling efficiency [16].

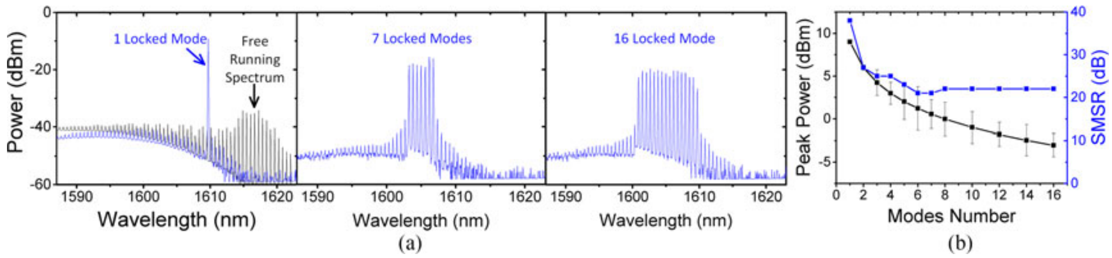

Fig. 2. Self-injection locking characteristics of Qdash-LD, measured at 2% output of the coupler. (a) Single locked mode along with the free running spectrum, 7, and 16 locked modes, and (b) variation of the mode peak power and SMSR with the number of self-locked FP modes. SMSR in this case is defined as the ratio of the average mode peak power of the FP modes within the BPF pass band to the highest mode peak power of the FP mode outside the BPF pass band.

3. Self-Injection Locking Characterization

Self-injection locking on Qdash-LD is investigated according to the arrangement shown in Fig. 1(a). The SMF coupled laser power is directed to an EDFA via port 2 of the optical circulator (OC), from which 50% of the power is fed back into the laser via a 3 dB coupler (CP), while the remaining 50% is utilized for subsequent transmission experiments. A tunable band pass filter (BPF) is connected in the feedback path to selectively control single (multiple) FP mode(s) power to be re-injected into the laser active region via port 3 of the OC for locking purpose. An EDFA (Amonics AEDFA-L-18B-R) with fixed 20 dB gain, operating in 1570–1610 nm region, is employed to compensate for the SMF coupling loss and $\sim$7dB insertion loss of the BPF (Santec Optical Tunable Filter-350). The self-injection locking spectrum is monitored with an additional 2:98% CP by connecting the OSA to the 2% output of the CP.

Fig. 2(a) and (b) summarizes the self-injection locking results of $3 \times 600\ \mu m^2$ chirped Qdash-LD obtained at the 2% coupler output. The lasing spectrum depicts different numbers of self-injection locked FP modes, ranging from 1 to 7 and to 16, which is accomplished by tuning the BPF pass-band and central wavelength, to control the number of FP modes feedback power into the laser. It was noted that regardless of the variation in the number of locked modes, the integrated power of the Qdash-LD spectrum remained fixed at $\sim$10 dBm (observed at the 3 dB coupler output), which corresponds to an integrated power injection ratio of ~-20 dB at the laser facet end. The variation of the single mode peak power and the SMSR (defined as the ratio of the average mode peak power of the FP modes within the BPF pass band to the highest mode peak power of the FP mode outside the BPF pass band) due to increasing the number of self-locked FP modes is plotted in Fig. 2(b). A single (16) self-locked mode(s) exhibited $\sim$10 (~-2.5) dBm mode power and $\sim$38 ($\sim$22) dB SMSR, showing an apparent inverse behavior of these performance parameters with the number of self-locked modes. This is ascribed to the constant integrated output power from the Qdash-LD (i.e., the power in the self-locked loop) which considerably decreased the power injection ratio per FP mode from ~-20 dB (one locked mode) to ~-32 dB (16 locked modes) and hence caused inefficient locking. Besides, only half of the Qdash-LD emission coverage between $\sim$1600–$\sim$1610 nm is utilized in this work owing to the limitation posed by the EDFA extreme wavelength operation (up to 1610 nm) and its amplified spontaneous emission (ASE) peak at $\sim$1570 nm that starts to dominate when operated beyond $\sim$1610 nm. Deployment of an appropriate specification EDFA with an optimized Qdash-LD device structure would enable extended $>$1610 nm wavelength operation, thus incorporating tens of self-locked modes with enhanced multi-wavelength laser performance characteristics. Moreover, an alternative to the self-seeding arrangement (i.e., OC, BPF and CP) could be achieved using a custom designed tunable single fiber Bragg grating (FBG), to enable realization of a compact source for commercial deployment. Finally, short-term stability test was also performed on 1609.6 nm locked mode for over 20 minutes. A variation in mode power and SMSR of $<$0.2 dBm and $<$1 dB was observed, while the mode wavelength exhibited $\sim$0.06 nm change.

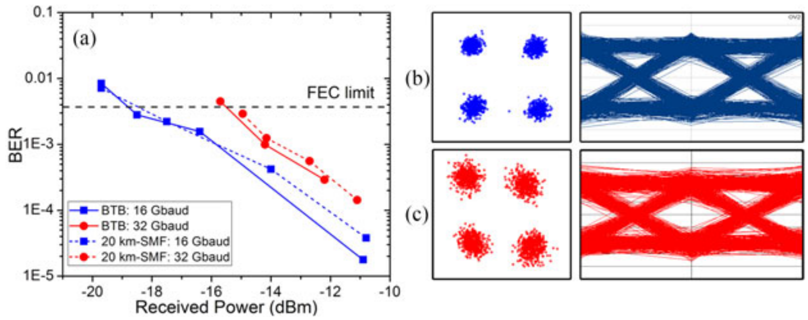

Fig. 3. Single 1609.6 nm self-locked FP mode transmission results. (a) Measured BER for 16 Gbaud (64 Gb/s) and 32 Gbaud (128 Gb/s) DP-QPSK signals over BTB and 20 km SMF transmission. The corresponding QPSK constellation and eye diagram of (b) 64 Gb/s and (c) 128 Gb/s at a received power of −11 dBm.

4. Optical Transmission Experiments

For the transmission experiments, a single self-injection locked FP mode is selected by tuning the BPF to 1609.6 nm, corresponding to a near central lasing wavelength of the Qdash-LD with mode power ∼10 dBm (measured at the 3 dB coupler output) and power injection ratio ∼−20 dB. This single optical subcarrier is then fed into an external DP-IQM, as shown in Fig. 1(a). We utilized a 65GSa/s arbitrary waveform generator (Keysight AWG M8195A) to obtain a pseudo random binary sequence (PRBS) with a pattern length of 211–1 and hence two QPSK signals to drive the modulator, while the pre-processing of the signal was performed using MATLAB. The modulated optical signal exhibited ∼−3 dBm integrated power which translates to ∼13 dB insertion loss of the modulator in mid L-band region. After traveling through 20 km long SMF, or BTB channel, the received signal is demodulated and analyzed using an optical modulation analyzer (Keysight OMA-N4391A). A variable optical attenuator (Agilent Technologies VOA-N7764A) is also utilized at the receiver terminal before demodulation to test the performance of the communication system by obtaining the bit error rates (BER) at various received power values.

Fig. 3(a) shows the performance of 1609.6 nm self-injection locked Qdash-LD mode over 20 km SMF, when modulated at two different data rates of 16 and 32 Gbaud. The results of error vector magnitude (EVM) BER in BTB configuration is also plotted alongside 20 km SMF results for comparison purpose. Error-free transmission with both the data rates of 64 and 128 Gb/s are accomplished with BER below the forward error correction (FEC) threshold of $3.8 \times 10-3$ and at minimum received powers of ∼−18 and ∼−16 dBm, respectively. Furthermore, a clear QPSK constellations and open eye diagrams of one polarization are depicted in Fig. 3(b) and (c) for both the data rates, at a received power of −11 dBm, thus affirming an effective communication. An eye opening factor (the ratio of the eye opening to the eye amplitude), eye width, eye jitter (peak-peak) and rising/falling time were measured to be 75(45)%, 47(23) ps, 15(8) ps and 50(20) ps, respectively, for 16 (32) Gbaud transmission, corresponding to a symbol period of 62.5(31.25) ps. Alternatively, minimum received powers of ∼−18 and ∼−16 dBm were achieved under BTB configuration, corresponding to a power penalty of mere ∼−0.5 dB compared to SMF transmission. Although, the used SMF displayed ∼0.3 dB/km loss at 1610 nm, a negligible difference in the power penalty might be attributed to the built-in dispersion compensation algorithms of the OMA that are employed at the receiver end to minimize the fiber dispersion, and hence maximize the transmission performance.

To stem the feasibility of employing Qdash-LD as viable source in 100G and 400G NG-PONs, we propose a single SMF bidirectional multi-subscriber WDM-PON architecture, shown in Fig. 4. The system is based on a single self-seeded Qdash-LD as a multi-wavelength down-streaming transmitter (with unified receivers) at the central office (CO) that would simplify the architecture. For upstreaming purpose, a unified tunable self-injection locked single FP mode Qdash-LD is employed at ONUs by tuning the BPF or compact FBG to appropriately select a particular FP mode

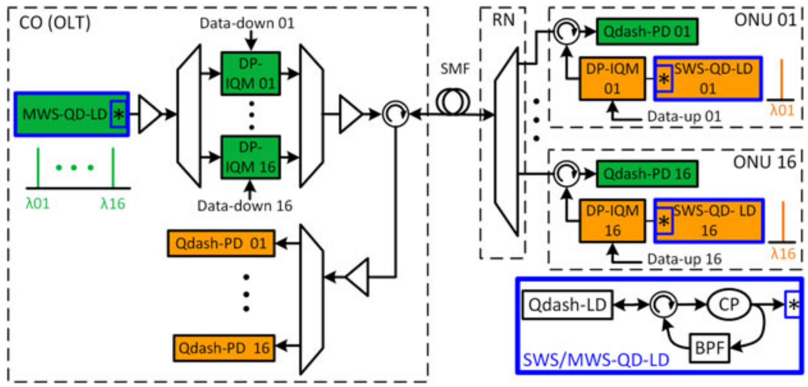

Fig. 4. Proposed WDM-PON architecture based on self-seeded Qdash-LD as a multi-wavelength source at CO (MWS-QD-LD) and broadly tunable single wavelength source at ONUs (SWS-QD-LD). The network displays a potential data capacity of 2 Tb/s (16 $\times$ 128 Gb/s) in mid L-band wavelength window. Note: BPF can be replaced with a custom designed tunable FBG to simplify the self-seeding arrangement.

TABLE 1
Power Budget for Proposed 2Tb/s WDM-PON With 128 Gb/s Bidirectional Transmission Capability

<table>
<tr><th>Parameter</th><th>Downstream</th><th>Upstream</th></tr>
<tr><td>Single subcarrier power (dBm)</td><td>−2.5</td><td>10</td></tr>
<tr><td>Total EDFAs gain (dB)</td><td>30 (2 stages)</td><td>12 (1 stage)</td></tr>
<tr><td>Total AWGs loss (dB)</td><td>15 (3 stages)</td><td>10 (2 stages)</td></tr>
<tr><td>DP-IQM loss (dB)</td><td colspan="2">13</td></tr>
<tr><td>20 km SMF loss (dB)</td><td colspan="2">6</td></tr>
<tr><td>Circulator and connectors losses</td><td colspan="2">3</td></tr>
<tr><td>Receiver sensitivity (dBm)</td><td colspan="2">−16</td></tr>
<tr><td>Power margin (dB)</td><td colspan="2">6</td></tr>
</table>

as an upstreaming optical carrier. Hence, deployment of self-seeded Qdash-LDs to achieve both, multi-wavelength Qdash-LD (MWS-QD-LD) as well as a broadly tunable single wavelength source (SWS-QD-LD), enables realization of unified transceivers alongside Qdash based photodiodes (Qdash-PD), thus significantly reducing the cost while providing flexibility and scalability. Moreover, based on the successful transmission of 128 Gb/s, the system could potentially provide an aggregate data capacity of 2 Tb/s if 16 FP modes are deployed as subscribers for both downstream and upstream data transmission or, 32 FP modes with separate 16 upstreaming and 16 downstreaming wavelengths. A power budget analysis of the proposed WD-PON is presented in Table 1 exhibiting a power margin of $\sim$6 dB for bidirectional data transmission. In addition, the power margin is expected to improve considerably by incorporating an efficient Qdash-LD with high power and optical bandwidth.

5. Conclusion

The concept of an L-band multi-wavelength source based on self-injection locked Qdash-LD was proposed and successfully realized showing the feasibility of this new-class of source as a promising candidate in NG-PONs. Controllable number of active channels from 1 to 16 is accomplished with peak power and SMSR variation of ∼10 to ∼−2.5 dBm and ∼38 to ∼22 dB, respectively. Error free DP-QPSK transmission of up to 128 Gb/s over 20 km SMF is demonstrated with a single 1609.6 nm mid L-band subcarrier. Subsequently, a simple and cost-effective WDM-PON architecture is proposed based on the transmission results, addressing 100G and 400G WDM access networks, with a prospective capacity of 2 Tb/s. Besides, the possibility of unifying the ONUs using broadly tunable single wavelength self-seeded Qdash-LD transmitters and single multi-wavelength source feeding several OLTs is also presented.

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