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Free-Running 1550 nm VCSEL for 10.7 Gb/s Transmission in 99.7 km PON

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***Abstract*—We present a cooler-less, free-running 1550 nm vertical cavity surface emitting laser (VCSEL) directly modulated at 10.7 Gb/s. We also report on error-free transmission through 40 km of standard single-mode optical fiber, achieved without the use of dispersion-mitigation or mid-span amplification. Inverse-dispersion fiber was utilized to realize a dispersion-matched 99.7 km optical access uplink supporting error-free transmission with 27 dB loss margin. These results indicate the feasibility of implementing cooler-less long-wavelength VCSEL devices in long-reach optical access networks.**

***Index Terms*—Passive optical network; Vertical cavity surface emitting laser.**

I. Introduction

Sustained increase in demand for broadband data services has motivated the expansion of modern data communications networks [1]. Additionally, bandwidth limitations of traditional copper-based or wireless data transmission schemes have encouraged the deployment of broadband optical transmission technologies in the access networking environment. Sustainable deployment of optical access networks requires reliable, inexpensive and energy-efficient broadband optical sources [2,3]; this has encouraged the development of low-cost laser sources for directly modulated optical links. Vertical cavity surface emitting laser (VCSEL) technology is a potential candidate for realizing low-cost broadband signaling sources. Un-cooled VCSEL units have been demonstrated supporting data rates of 10 Gb/s [4–6] and 20 Gb/s [7]; cooled VCSEL sources operating at 38 Gb/s [8] have also been presented. Injection locking has also been used to extend the transmission range achieved with directly modulated VCSEL devices. VCSEL sources have been operated at 10 Gb/s and demonstrated at 40 km [9]; longer range transmission has also been reported [6,10] with more sophisticated control of the chirp of the locked laser source.

We extend on our previous investigations [11–13] of the performance of a cooler-less 1550 nm VCSEL directly modulated at 10.7 Gb/s. We report on error-free transmission of the optical signal thus obtained over 40 km of standard single-mode fiber (SMF), without the use of any dispersion-mitigation techniques. For uncompensated transmission over 35 km and 40 km, we obtained error-free results with a pseudorandom binary sequence (PRBS) of length $2^7 - 1$ bits, with a receiver power level of −19 dBm; this is similar to the sensitivity levels reported by injection-locked systems operating at 10 Gb/s [9]. We also successfully transmitted the 10 Gb/s optical signal over an un-amplified 99.7 km dispersion-matched link, in which a field-deployable inverse-dispersion fiber (IDF) was used for dispersion compensation; no other dispersion-mitigation technique was used for this analysis. IDF has a dispersion profile which is the inverse [14,15] of G.652 standard SMF. We obtained error-free data transmission with a bit error rate (BER) below 10^{-9}. To assess the influence of pattern-length dependencies, the data signal was generated using PRBSs of varying lengths. Error-free transmission was also achieved over the dispersion-matched 99.7 km uplink when a PRBS of length $2^{31} - 1$ bits was used. Our results show the feasibility of long-wavelength VCSELs in the deployment of enhanced range passive optical network (PON) systems, and also highlight the applicability of IDF in extending the range of broadband optical networks.

The remainder of this paper is structured as follows: we present the characterization of the VCSEL in Section II, and present the description of the PON uplink evaluation in Section III. Significant system results are presented in Section IV; concluding remarks are presented in Section V.

II. VCSEL Characterization

The VCSEL used in this experiment was operated without any temperature stabilization or control circuitry. We assessed the DC characteristics of the VCSEL source and obtained the power versus bias current response presented in Fig. 1. The maximum rated bias current for this device was specified at 19 mA; we observed a lasing threshold current of 3 mA. When a bias current of 18 mA was applied, the VCSEL provided +1 dBm average optical output power.

Laser operation was not optimized for the maximum optical extinction ratio, since this condition also resulted in increased overshoot and ripple in the output waveform, indicating a highly chirped optical signal. Indeed, such a chirped optical signal would have increased sensitivity to dispersion; this would limit the maximum transmission distance before dispersion compensation becomes necessary. The laser was biased far from threshold, and the modulating waveform was adjusted to provide large optical extinction without output ripple.

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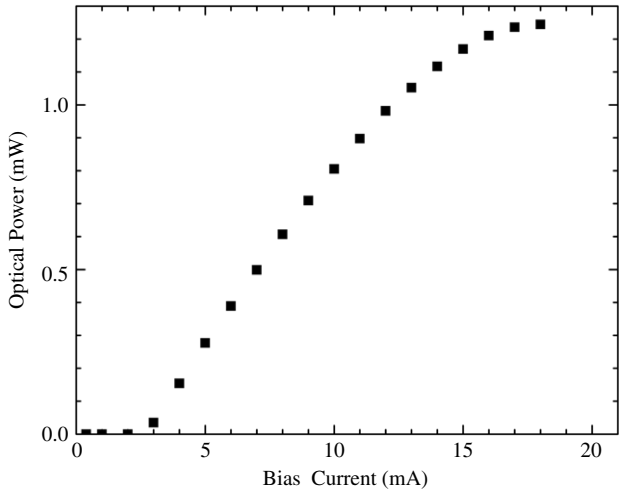

Fig. 1. DC characteristic of the VCSEL source used for this evaluation.

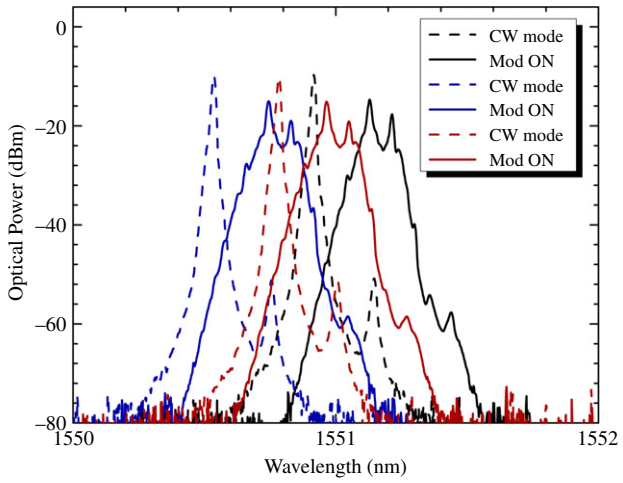

Fig. 2. (Color online) Back-to-back optical spectrum of the VCSEL with a 10.7 Gb/s NRZ-OOK data signal as the VCSEL operated at ambient temperature within the laboratory. The lasing wavelength was observed to drift during the experiment (measurement resolution: 0.01 nm).

With the laser biased at 11.36 mA, we applied a 10.7 Gb/s non-return-to-zero on–off keying (NRZ-OOK) modulating signal with 0.54 mV amplitude. An optical extinction ratio of 5.85 dB was observed at the VCSEL output; this signal had an optical signal-to-noise ratio (OSNR) of 7.43 dB and average optical power of −1 dBm.

During the course of the experiment, the continuous-wave (CW) lasing wavelength of the un-cooled device varied between 1550.5 and 1550.9 nm; when modulation was applied, the peak wavelength increased by approximately 0.3 nm and was observed to vary between 1550.8 and 1560.1 nm over the course of the experiment. Figure 2 presents typical optical spectra of the laser output observed over the course of the experiment; the blue and black traces represent extreme values observed in the excursion of the laser output wavelength; the red trace indicates median observations. Dashed traces indicate CW mode operation and the solid lines reflect laser output when modulation was activated (Mod ON).

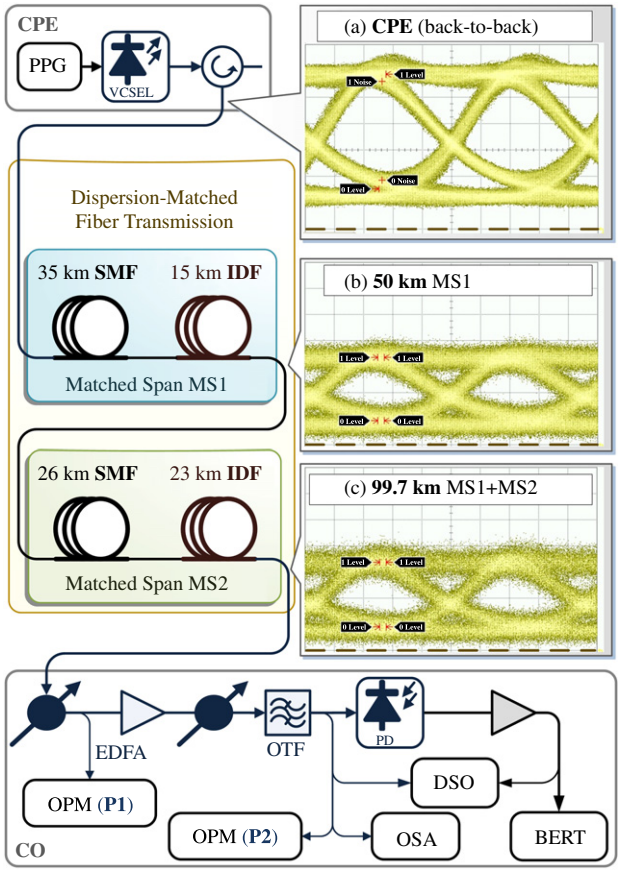

Fig. 3. (Color online) System layout: a free-running cooler-less VCSEL at the customer premises equipment (CPE) transmits a NRZ-OOK data pattern at 10.7 Gb/s to a receiver at the central office (CO) via dispersion-matched spans (MS1 and MS2) of transmission fiber. BERT, bit error rate test; DSO, digital storage oscilloscope; OSA, optical spectrum analyzer; OTF, tunable optical bandpass filter (0.9 nm FWHM); PPG, pulse pattern generator. The power levels P1 and P2 were controlled during the evaluation. The insets show optical eye observations at 20 GHz bandwidth: (a) at CPE output, (b) after 50 km MS1 and (c) after 99.7 km cascaded MS1 and MS2. The dotted lines show the zero level. Vertical scale: (a) 150 μW/div. (b,c) 50 μW/div. Horizontal scale: (a,b,c) 20 ps/div.

III. Passive Optical Network (PON) Uplink

We emulated the uplink of an extended-reach passive optical network using the setup shown in Fig. 3. The customer premises equipment (CPE) consisted of a free-running VCSEL that was directly modulated by an NRZ-OOK data signal from a pulse pattern generator (PPG); a dual-drive configuration was applied at the VCSEL input, using the differential data signals obtained from the PPG. The VCSEL used in this experiment operated without temperature stabilization. A circulator was used to prevent back-scattered optical energy from entering the laser cavity; in practical systems this circulator would facilitate bidirectional communication over a single fiber.

TABLE I
CHARACTERISTICS OF OPTICAL MEDIA USED (1550 NM WAVELENGTH)

Fiber type	SMF G.652	IDF (MS1) IDF × 2	IDF (MS2) IDF × 1
Dispersion (ps/nm · km)	16.5	−39.9	−20.8
Dispersion slope (ps/nm^2 · km)	0.058		
RDS[a] (nm^{-1})	0.0036	0.0032	0.0032
Attenuation (dB/km)	0.2	0.255	0.235
Mode field diameter (μm)	10.4	6.3	6.9
Effective area (μm^2)	82	30	36
PMD (ps/$\sqrt{\text{km}}$)	0.06	0.062	0.059
Cable cutoff (nm)	1260	1250	1340

Notes.
Values specified at 1550 nm operating wavelength.
[a] Relative dispersion slope.

Two types of transmission fiber were implemented in dispersion-matched sets of SMF and IDF. The SMF used in this evaluation had a specified unit dispersion of 17 ps/nm · km at 1550 nm wavelength. The first matched span, MS1, was composed of 35.3 km SMF and 14.8 km IDF; the total dispersion (D) of MS1 was −0.59 ps/nm (at 1550 nm wavelength). The second matched span, MS2, consisted of 26.4 km SMF and 23.3 km IDF; D was −1.7 ps/nm (at 1550 nm). An IDF × 2 type fiber was used in MS1, and MS2 implemented a type IDF × 1 fiber; both have previously been described in the literature [14,15]. Table I presents a summary of the optical properties of the optical media, within the operating wavelength range. The net insertion losses of MS1 and MS2 were 12.84 dB and 13.05 dB, respectively.

We implemented a pre-amplified receiver at the central office (CO) using an erbium-doped fiber amplifier (EDFA) with 35 dB gain and a noise figure of 4.2 dB. An optical tunable filter (OTF) with 0.9 nm full width at half-maximum (FWHM) was used to remove unwanted amplified spontaneous emission (ASE) noise and improve the OSNR at the 10 GHz PIN photodetector (PD). An average optical power of −9 dBm was maintained at the PD input, which was well within the linear response range of the device.

The filter FWHM was sufficiently large to allow the entire modulated signal through to the PD, while eliminating much out of band ASE. However, since the laser output wavelength drifted during the experiment (as shown in Fig. 2), the optical spectrum of the PD input was continually monitored during the experiment to make sure no benefit from offset filtering was exploited. Offset between the laser and the OTF passband spectra will result in asymmetric filtering of the chirped optical signal from the directly modulated laser; the resulting frequency-to-intensity conversion will distort the PD input in a manner that can improve the extinction ratio of the PD input, provided that the OTF passband is correctly tuned relative to the laser spectrum. An OTF with a large FWHM accommodating the entire VCSEL drift range is preferable, as this would provide a more generalized receiver structure, as would be the case in wavelength division multiplexed (WDM) PONs using 50 GHz spacing. For this analysis, therefore, care was taken to ensure that the OTF passband was always centered on the received optical spectrum. Under these conditions, the OTF only improved the OSNR at the receiver by rejecting out of band ASE, but performed no dispersion compensation or frequency-to-intensity mapping. Discussions of asymmetric optical filtering in directly modulated links appear in the literature [11,12,16].

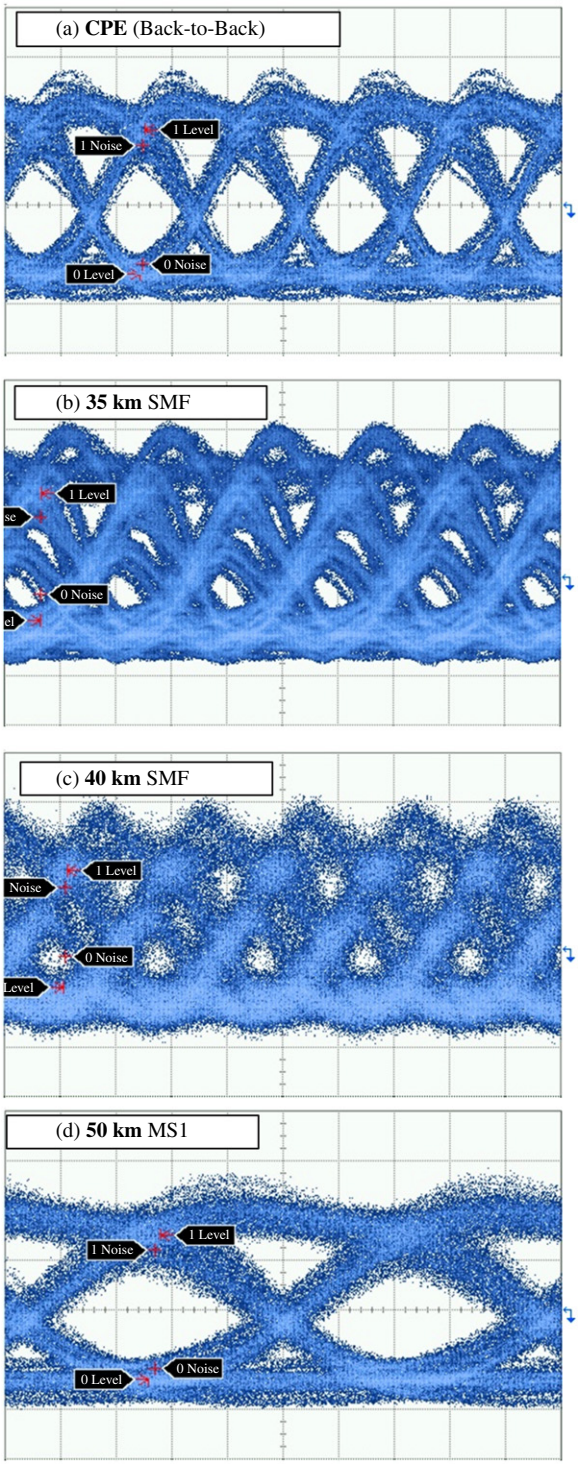

Fig. 4. (Color online) Post-PD electrical eye diagrams with 10.7 Gb/s NRZ-OOK signal, taken using a 10 GHz PD. Observations made: (a) back to back at CPE, (b) after 35 km uncompensated SMF, (c) after 40 km uncompensated SMF, and (d) after 50 km of matched span MS1. Vertical scale: (a,b,c,d) 300 mV/div. Horizontal scale: (a,b,c) 50 ps/div., (d) 20 ps/div.

TABLE II
EXTINCTION RATIO AND OSNR AT KEY POINTS ALONG THE PON UPLINK

Observation Point	Extinction Ratio (dB)	OSNR (dB)
CPE output	5.88	7.45
35 km SMF	4.73	2.80
40 km SMF	4.61	2.70
MS1 (50 km total)	5.79	5.07
MS1 + MS2 (99.7 km total)	6.01	4.71

Notes.
OSNR was assessed using signal eye observations on the DSO.

IV. KEY RESULTS

We assessed the optical signal obtained at key points within the system, and utilized PRBSs of varying length to assess system sensitivity to pattern-length-dependent effects. Observations of the propagating signal were made after 35 km SMF, 40 km SMF and after dispersion-compensated transmission over 50 km (MS1) and 99.7 km (MS1 and MS2) of optical fiber. The eye diagrams obtained were not observed to vary significantly with change in the PRBS used. Using a PRBS of length $2^7 - 1$ bits, we observed the eye diagrams on an oscilloscope, using the 20 GHz internal photodetector, and present the traces in Fig. 4. Unless otherwise noted, the optical power level into the pre-amplifier was controlled at −20 dBm, and the optical power into the PD at −9 dBm. Table II presents the optical extinction ratio and optical signal-to-noise ratio observations at these key points within the transmission uplink.

A clear open eye was observed at the CPE output, as shown in Figs. 3(a) and 4(a). We observed the degradation in OSNR associated with transmission over uncompensated SMF, as shown in Figs. 4(b) and 4(c) for 35 km and 40 km lengths, respectively. Although clear distinction can be made between low and high levels in the diagram, the eye of the propagating signal waveform was closed by ringing effects, which introduced vertical transitions close to the center of the bit period; these effects are a result of dispersion-induced inter-symbol interference. The signal observations at the outputs of the 50 km (MS1) and 99.7 km (cascaded MS1 and MS2) lengths of dispersion-matched fiber indicate good signal recovery at the receiver; clear open eyes and good OSNRs were observed. An improved extinction ratio was observed after the 99.7 km of cascaded fiber: the net negative chromatic dispersion of the link improves the directly modulated optical signal from the laser; this observation agrees well with other reports [17]. The OSNR was, however, degraded by 2.38 dB by transmission along MS1, and a further 0.36 dB by transmission over the second matched span (MS2). This was due to the EDFA at the pre-amplified receiver, which was optimized for low-noise amplification of low-intensity optical signals, and hence did not linearly degrade the OSNR as the input power level was decreased. The open eye obtained after the cascaded 99.7 km matched span suggested feasible data communications over this link; we therefore extended our investigation by assessing BER sensitivity to received signal power.

We assessed data transmission through this uplink by evaluating BER sensitivity. PRBSs of varying lengths were used to evaluate pattern-length-dependent system response. The results of the BER sensitivity assessment are presented in Fig. 5. Solid black symbols indicate results obtained at the CPE output, unfilled blue symbols identify results after 35 km SMF, and blue symbols with crosses show results after 40 km SMF. Red (top half-filled) symbols indicate results at MS1 output, and green (left half-filled) symbols indicate results after 99.7 km cascaded MS1 and MS2. We distinguish between PRBSs of various lengths by using the same shape for each PRBS length: 2^7-1 (circle), $2^{15}-1$ (square), $2^{23}-1$ (upward pointing triangle) and $2^{31}-1$ bits (downward pointing triangle).

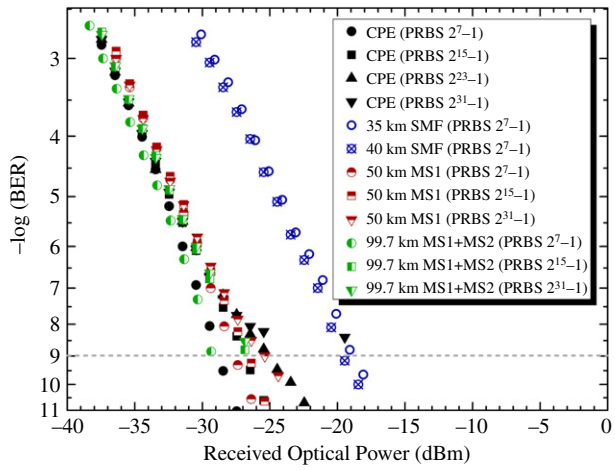

Fig. 5. (Color online) BER sensitivity for 10.7 Gb/s signal at key points throughout the transmission link. PRBSs of various lengths (2^7-1, $2^{15}-1$, $2^{31}-1$) were used to evaluate the system. (The dotted line indicates the error-free threshold at BER = 10^{-9}.)

For the signal obtained directly from the CPE, error-free results were obtained with −29 dBm of received optical power, when a PRBS of length $2^7 - 1$ bits was used. Approximately 2 dB of power penalty was observed with a PRBS of length $2^{15} - 1$ bits, and 4 dB of penalty was observed with a PRBS of length $2^{23} - 1$ bits. Under this back-to-back condition, a BER floor close to 5×10^{-8} was observed with a PRBS length of $2^{31}-1$ bits. This indicates that the transmitter is susceptible to pattern-length-dependent effects, likely due to the presence of long runs of successive ones and zeros in the modulating signal waveform. These cumulatively vary the bias point of the device around the desired value, thus distorting the optical properties of the laser output waveform.

For the uncompensated transmission over 35 km and 40 km, we obtained error-free results with the shortest PRBS, at received power levels of approximately −19 dBm. With 35 km and 40 km SMF, a BER floor was observed at 1×10^{-3} and 6×10^{-3}, respectively, when a PRBS of length $2^{15} - 1$ bits was used. Although previous work had produced shorter dispersion-limited link lengths [11,12], subsequent efforts led to the realization that the selection of laser bias far away from threshold, along with a larger amplitude input electrical signal than previously employed, produced an optical output signal that was suitable for longer range optical transmission before dispersion compensation became necessary [13]. We were thus able to exploit these electrical drive conditions to achieve error-free transmission of this data signal over 40 km of uncompensated SMF. These results for the PRBS

of length $2^{15} - 1$ bits over 40 km of uncompensated SMF compare favorably with the sensitivity levels reported with an injection-locked VCSEL source [9], which is encouraging as our transmitter did not require any injection locking. As signaling formats used for access links (including IEEE 802.11 Ethernet-based schemes) implement safeguards to prevent the appearance of such long runs of consecutive zero or one bits, system performance with the short PRBS indicates the feasibility of implementing 10 Gb/s communications links over uncompensated 40 km SMF. The inclusion of IDF into the link was observed to improve system performance, with increased receiver sensitivity over the uncompensated transmission. With the IDF, we were able to recover error-free transmissions for all PRBSs used. The net negative dispersion of the matched transmission spans was observed to improve transmission performance beyond that obtained at the transmitter output; this result does not conflict with previously reported results for transmission of directly modulated laser signals over links with net negative chromatic dispersion [17].

V. Conclusion

We have presented results on the characterization of a novel VCSEL device that can be directly modulated at 10.7 Gb/s, and the output signal can be transmitted error-free over 40 km of uncompensated SMF with a receiver sensitivity of −29 dBm when a PRBS of length $2^7 - 1$ is used. Field-deployable IDF fiber was used to implement an extended range 99.7 km PON uplink; error-free transmission was also achieved over this link. Less than 3 dB penalty was observed when a PRBS of length $2^{31} - 1$ bits was used over the same length transmission span, which is consistent with reported assessments of optical transmission over negative-dispersion fiber.

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