# 480Mbit/s UWB bi-directional radio over fiber CWDM PON using ultra-low cost and power VCSELs

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**Abstract:** Radio-over-fiber (RoF) schemes offer the possibility of permitting direct access to native format services for the domestic user. A low power requirement and cost effectiveness are crucial to both the service provider and the end user. Here, we present an ultra-low cost and power RoF scheme using direct modulation of commercially-available 1344 nm and 1547 nm VCSELs by band–group 1 UWB wireless signals (ECMA-368) at near broadcast power levels. As a result, greatly simplified electrical-optical-electrical conversion is accomplished. A successful demonstration over a transmission distance of 20.1 km is described using a SSMF, CWDM optical network. EVMs of better than −18.3 dB were achieved.



**OCIS codes:** (060.0060) Fiber optics and optical communications; (060.1155) All-optical networks.

## References and links

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## 1. Introduction

Radio-over-fiber schemes offer the distinct advantage of direct access to the native formats being offered by service providers. This enables the use of standard commercial equipment without the need for additional signal conditioning. When considering the deployment of devices, power consumption and optical power output is an important factor for service providers and domestic users alike. The use of low power VCSELs can offer optical power levels acceptable for domestic use. Low power consumption is also attractive to service providers when considering device deployment in the exchange or roadside cabinet where power consumption is a critical factor. Radio standards such as UWB, WiMAX, LTE, WLAN, DVB-T or DAB use orthogonal frequency division multiplexing (OFDM) whilst UWB features a multi-band configuration (MB-OFDM). The relative immunity to multi-path fading is an intrinsic characteristic of MB-OFDM modulation but is achieved at the expense of large peak-to-average power ratio (PAPR, ~9 dB). In MB-OFDM UWB systems, limiting the transmit power to −41.3 dBm/MHz results in an average transmit power of −9.5 dBm.

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Therefore 9 dB PAPR results in a peak transmit power of −0.5 dBm, which is realizable in CMOS technology without the need for an external power amplifier [1]. Such signals can directly modulate latest generation, commercially–available, un-cooled VCSELs (e.g., Vertilas VL-1344/1547-10G-P2-H4). However use in off-air applications may require additional amplification stages, hence imposing a cost-disincentive.

In this paper, we report off-air, bi-directional, radio-over-fiber (RoF) transmission of MB-OFDM based, 480 Mbit/s UWB signals over a 20.1 km coarse wavelength division multiplexed (CWDM) passive optical network (PON). The low component count features of such a PON offer ultra-low cost and allows the use standard equipment at both ends of the architecture [2]. Simultaneous paths in opposite directions at 1344 nm and 1547 nm provided 480 Mbit/s band-group 1 (3.168 GHz to 4.752 GHz) UWB with an EVM of < −18.3 dB compared to the standard pass level of < −17 dB. With the goal of interfacing standard (ECMA-368 compliant) UWB equipment to optical devices with a minimum component count, such an EVM enables direct re-transmission in the RF domain. The low modulation amplitudes required by the VCSELs also facilitates the direct interfacing of commercial domestic UWB equipment. Opportunities are therefore available for RoF PON networks at beneficial cost-performance ratios whilst fulfilling current end-user radio standard specifications.

## 2. Theoretical considerations

The experimental configuration presented here may be regarded as a subcarrier transmission system. These have received much attention over time (e.g., [3].). It is possible to analyze the effects on EVM of the various thermal, laser relative intensity, phase jitter and composite second and third order intermodulation noise and distortion sources. This brief theoretical discussion shows that it is difficult to achieve EVMs much better than the measured figures (typically −22.5dB) without using unrealizable laser modulation indices. The following heuristic method below is based on [3].

EVM is assumed to be proportional to VCSEL modulation index $m$ and mean-square photo-current $< m^2 I_{ph}^2 >$. It is reduced in a bandwidth B by thermal noise current $< I_{ph}^2 B >$, shot noise $< 2 e I_{ph} B >$ with e the electronic charge, relative intensity noise (RIN) $< I_{ph}^2 RIN B >$, phase noise $< I_{ph}^2 \Phi^2 B >$; where $\Phi$ is the r.m.s phase noise and composite triple-beat noise $< I_{ph}^2 m^6 C_3 >$ where $C_3$ is the third-order distortion coefficient. As will be shown later there is little second-order contribution as less than an octave bandwidth is occupied. Overall, we have in Eq. (1)

$$EVM \,\alpha\, \frac{\langle I_{th}^2 \cdot B\rangle + \langle 2\, e\, I_{ph}\, B\rangle + \langle I_{ph}^2 \cdot RIN \cdot B\rangle + \langle I_{ph}^2\, \Phi^2 \cdot B\rangle + \langle I_{ph}^2\, m^6\, C_3\rangle}{\langle m^2 I_{ph}^2\rangle} \qquad (1)$$

or

$$EVM \,\alpha\, \frac{\langle I_{th}^2 \cdot B\rangle + \langle I_{ph}^2\rangle \langle RIN.B + \Phi^2 \cdot B + m^6\, C_3\rangle}{\langle m^2 I_{ph}^2\rangle} \qquad (2)$$

From Eq. (2), and in the absence of distortion, it is clear that EVM is ultimately limited by RIN and phase noise with a relatively large $I_{ph}$ for a given $m$. However, this is an ideal case and the experimental results presented here are expected to be limited by thermal and shot noise. Nevertheless, it is possible to minimize EVM (a desirable outcome) for a given $m$ as $\partial(EVM)/\partial m = 0$. This leads to Eq. (3):

$$EVM_{\min} = 3 m_{opt}^4\, C_3 \qquad (3)$$

where $m_{opt}$ is optimum modulation index. This elegant result is possible because many of the terms are taken as independent of $m$. As an example, if −30dB EVM is required (c.f −22.5dB

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in practice) with $C_3$ = 0.1, then $m_{opt}$ = 0.24. This may be compared with a typical experimental VCSEL modulation index of 0.1 which produces third harmonic terms at approximately -43 dBc. Thus the experimental measurements are not limited by distortion effects.

## 3. Experimental setup

The latest-generation VCSELs used in this experiment need to be particularly well-matched to 50 Ω if the low power drive aspects are to be fully–realized. This criterion is a re-statement of the classical power-factor issue, whereby the delivered (real) power P is given by $P = V \cdot I \cdot \cos(\theta)$. Here $V \cdot I$ is the apparent power, $\cos(\theta)$ the power factor and $\theta$ the phase angle between $V$ and $I$. The typical VCSEL input impedance was measured as 48.6 Ω - j 1.5 Ω at 5.7 GHz which determines $\theta$ as 1.89 degrees and equates to a power factor of 99.9%; highlighting the ultra-low power aspect of the experiment. Figures 1(a)–1(d) below show the $S_{11}$ forward reflection, Smith chart plots and $S_{21}$ forward transmission, frequency response plots for both the 1547 nm and 1344 nm VCSELs across a frequency range from 40 kHz to 10 GHz. An out-of-band resonant effect at 5 GHz and 5.6 GHz for the 1547nm and 1344 nm VCSELs respectively is apparent in Figs. 1(c) and 1(d) whilst the corresponding Smith chart impedance migration is shown in Figs. 1(a) and 1(b).

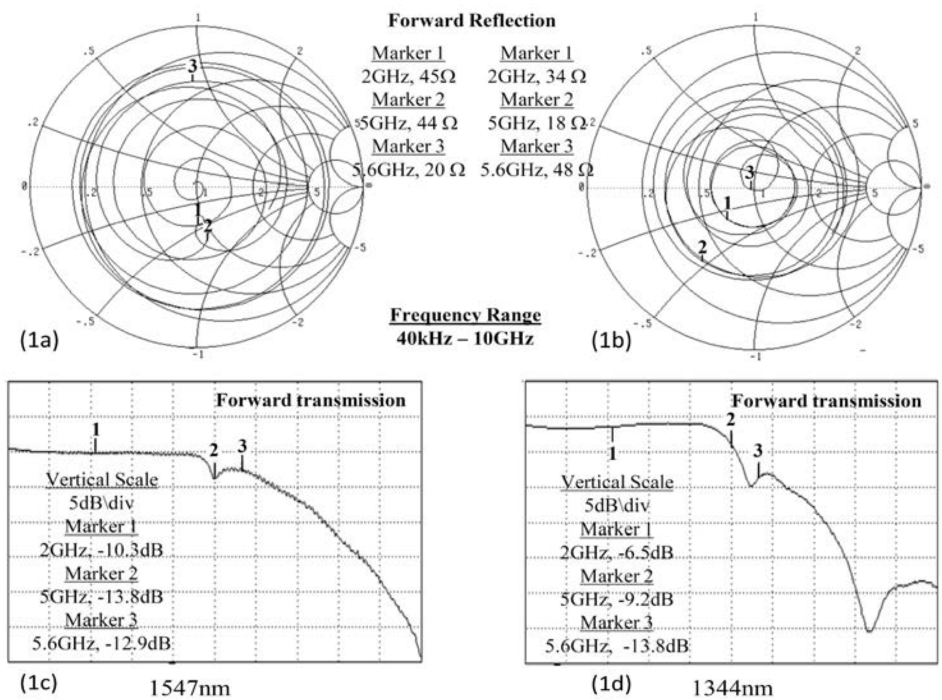


Fig. 1. (a) 1547 nm VCSEL $S_{11}$ Smith chart, (b) 1344 nm VCSEL $S_{11}$ Smith Chart, (c) 1547 nm VCSEL $S_{21}$ Transmission frequency response, and (d) 1344 nm VCSEL $S_{21}$ Transmission frquency response.

A complete bi-directional experimental demonstration system was set up as in Fig. 2 below. As shown, the radio part of the experimental set-up comprised a pair of UWB transducers (standard UWB dongles from Belkin) with the off-air signal being extracted by a power splitter (Mini-Circuits ZN4PD1-50). A signal power of −44 dBm, is typical of the level to be found in 2-m separation MB-OFDM UWB links. With the use of RF attenuators the signal level could be varied from −60 dBm to −33 dBm into 50 Ω. After passing through a bias-tee, this signal was used to directly modulate the 1547 nm VCSEL (Vertilas VL-1547-

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10G-P2-H4) as shown. An optical output power of −4.7 dBm at 8 mA bias, was measured prior to the CWDM splitter (LAS-10-086) which provided 40 dB isolation from the return 1547 nm channel. The output signal was then passed to a link of up to 20.1 km of standard single mode fiber (SSMF) which comprised the transmission medium throughout the experiment. In the return path, a 1344 nm VCSEL (Vertilas VL-1344-10G-P2-H4) was used which offered –3.2 dBm launch power at 8 mA bias. Signal detection was accomplished using 10 GHz bandwidth photodiodes (Discovery DSC-R402AC) followed by a further RF amplifier (Atlantec AOX-010200) giving a combined amplification of 47 dB with a total receiver power consumption of 1125mW.

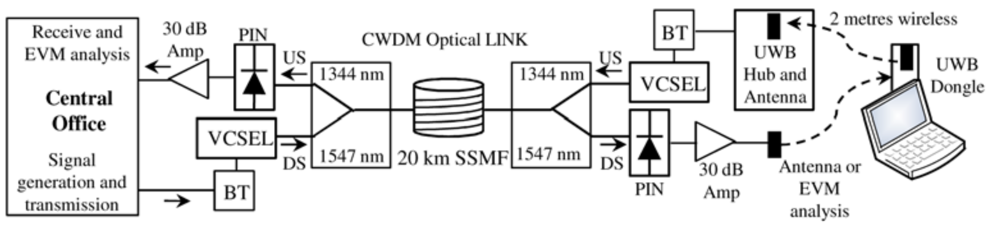


Fig. 2. System diagram showing two-way transmission path.

As mentioned above, UWB signal generation was provided by fully-WiMedia compliant, MB-OFDM USB dongles using time frequency code TFC6 (center frequency at 3.96 GHz with 528 MHz bandwidth), and dual-carrier modulation (DCM [1]) at 480 Mbit/s. The detected UWB signals were analyzed by a Tektronix DPO 71254 real time oscilloscope allowing capture of UWB bursts as they occurred. Figure 3 shows the electrical spectrum and constellations of the directly-modulated 1344 nm and 1547 nm VCSELs respectively at the launch point. As described, the technique of spectral analysis and constellation acquisition was used for all subsequent experimental investigation.

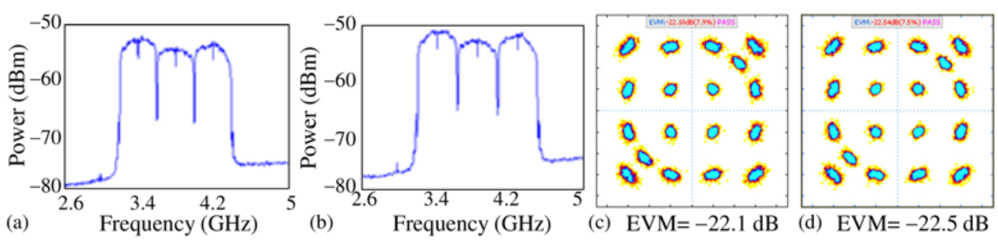


Fig. 3. Electrical spectra at launch VCSEL of (a) 1344 nm and (b) 1547 nm. Constellations at launch point working with: (c) 1344 nm and (d) 1547 nm.

## 4. Experimental results

Having determined that acceptable performance with low-level direct modulation signals was available, the EVM versus drive level was measured for both 1344 nm and 1547 nm VCSELs. As shown in Fig. 4 below, a resolvable –15 dB EVM was obtained even with –60 dBm direct modulation which corresponds to just $4.5\mu A/\sqrt{MHz}$ r.m.s current drive into 50 Ω. A lowest operational level of -44 dBm ( $28\mu A/\sqrt{MHz}/50\Omega$ ) was chosen after exploring direct modulation powers up to -30 dBm ( $141\mu A/\sqrt{MHz}/50\Omega$ ). VCSEL launch power with 12 mA bias increased to –1.5 dBm and –2.8 dBm for the 1344 nm and 1547 nm devices respectively. As can be seen in Fig. 4, the EVM ranged from a substandard -15 dB level at -60 dBm drive through an acceptable -20 dB value [4] further improving to approximately -23.5 dB at -30 dBm drive level. It was interesting to note that both 1344 nm and 1547 nm VCSELs gave similar results and suggests that drive signal level is not particularly critical.

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Furthermore, little further enhancement in EVM was achieved with increasing drive level as nonlinear contributions began to appear. This was to be expected from prior observations of other devices [5].

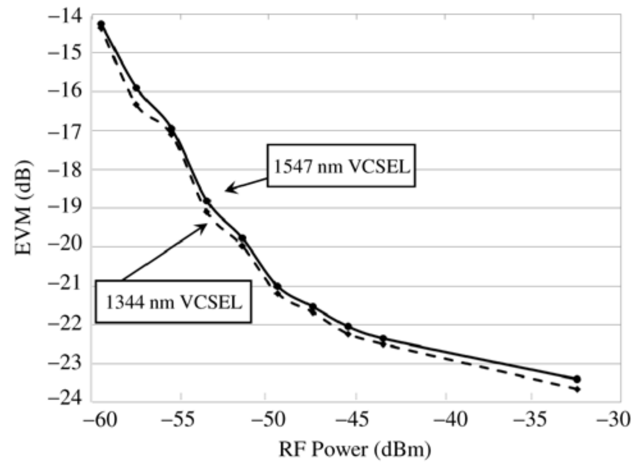


Fig. 4. EVM against UWB drive level for 1344nm and 1547nm VCSELs at 12 mA bias.

Figure 5 below shows the experimental results obtained at 1344/1547 nm when the fiber length was increased to 12.5 km. In this case, the received optical power was measured to be −8.8 dBm and −7.2 dBm at 1344/1547 nm respectively with 8mA VCSEL bias and a UWB RF drive level of –44 dBm. Figures 5(a) and 5(b) show the respective 1344 nm and 1537 nm detected RF spectra in the set-up of Fig. 2. Some higher frequency roll-off is evident in the 1547 nm VCSEL detected spectrum whilst the 3 bands in band group 1 are clearly defined. Additionally, the constellations in Figs. 5(c) and 5(d) show some degradation compared to Fig. 3 but are still completely viable with EVMs of –21.0 dB and –18.5 dB at 1344/1547 nm respectively. Figure 6 shows the 20.1 km case, both the 1344 nm and 1547 nm VCSEL bias and UWB RF drive levels were increased to 12 mA and –32 dBm (112 µa r.m.s into 50 Ω respectively. This improved the frequency response in the 5 GHz region as shown in Figs. 6(a) and 6(b), and in particular, the higher bias level enhanced the 5 GHz performance of the 1547 nm VCSEL by ~5 dBm. As mentioned above, VCSEL launch power with the 12 mA bias increased to –1.5 dBm and –2.8 dBm for the respective 1344 nm and 1547 nm devices. In this case, the received optical powers were –10.4 dBm and –6.9 dBm at 1344/1547 nm.

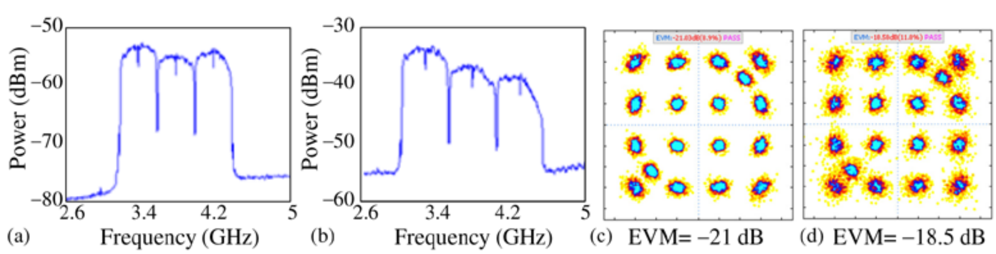


Fig. 5. Electrical spectrums after 12.5 km at: (a) 1344 nm and (b) 1547 nm. Constellations after 12.5 km: (c) 1344 nm and (d) 1547 nm.

Also as shown in Figs. 6(c) and 6(d), some further degradation in the 1344/1547 nm 16QAM constellations is evident, suggesting that an optimum performance level has been reached. However, the measured EVMs at −18.8 dB and −18.3 dB still meet the required −17 dB EVM target [1].

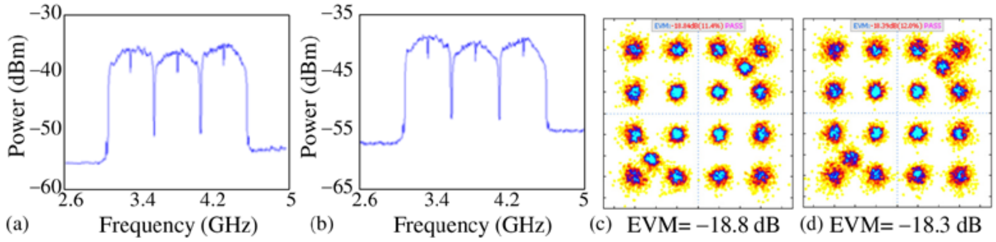


Fig. 6. Electrical spectrums after 20.1 km at: (a) 1344 nm and (b) 1547 nm. Constellations after 20.1 km: (c) 1344 nm and (d) 1547 nm.

## 5. Conclusions

We have demonstrated, for the first time, the successful use of ultra-low power 480 Mbit/s, MB-OFDM UWB signals to directly modulate low–cost, commercially–available, VCSELs in CWDM bi-directional radio-over-fiber transmission application. With drive signal levels in the range −60 dBm to −32 dBm, the results reported here show that virtual direct off-air modulation of current –generation, long-wavelength VCSELs is possible. In all cases, even up to 20.1 km reach in a 1344/1547 nm CWDM PON, EVMs of at least −18.3 dB were measured, compared to the baseline standard requirement of −17 dB. Considering the ultra-low power and cost aspects of the prototype networks demonstrated here, opportunities for embedded system approaches become available. Large scale deployment is then possible and this will be the subject of further investigation.

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