Direct high-frequency modulation of VCSELs and applications in fibre optic RF and microwave links

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Abstract. With the rapid development of wireless communication networks there is an increasing demand for efficient and cost-effective transmission and distribution of RF signals. Fibre optic RF links, employing directly modulated semiconductor lasers, provide many of the desired characteristics for such distribution systems and in the search for cost-effective solutions, the vertical cavity surface emitting laser (VCSEL) is of interest. It has therefore been the purpose of this work to investigate whether 850 nm VCSELs fulfil basic performance requirements for fibre optic RF links operating in the low-GHz range. The performance of single- and multimode oxide confined VCSELs has been compared, in order to pin-point limitations and to find the optimum design. Fibre optic RF links using VCSELs and multimode fibres have been assembled and evaluated with respect to performance characteristics of importance for wireless communication systems. We have found that optimized single-mode VCSELs provide the highest performance and that links using such VCSELs and high-bandwidth multimode fibres satisfy the requirements in a number of applications, including cellular systems for mobile communication and wireless local area networks.
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1. Introduction

Due to high performance combined with low manufacturing cost, the vertical cavity surface emitting laser (VCSEL) has become an established light source in data communication networks (local area networks (LANs) and storage area networks (SANs)) where the VCSEL is on–off modulated for the transmission of digital signals [1]. With the rapid developments of wireless communication networks there is also an increasing demand for simple, power-efficient and cost-effective transmission and distribution of RF signals over optical fibres. One such example is distributed antenna systems (DAS) for in-building coverage in cellular systems for mobile communication and wireless LANs (W-LANs), operating in the 1–5 GHz range [2]. While VCSELs fulfil the performance requirements of on–off modulated digital links at bit rates well in excess of 10 Gbit s\(^{-1}\) [3, 4], it is not obvious that they also fulfil the requirements of analogue links operating in the GHz range, since such links are in some aspects more demanding. Laser characteristics of particular importance for analogue links are the impedance, modulation efficiency, linearity and intensity noise. These laser parameters often limit the dynamic range, the gain, and the noise figure of analogue fibre optic links [5]. Earlier reports on the analogue modulation characteristics of VCSELs can be found in [6]–[10].

It has therefore been the purpose of this work to study the dynamics of standard oxide confined 850 nm VCSELs under direct high-frequency modulation and to determine whether they fulfil basic performance requirements for fibre optic RF links in wireless communication. Such VCSELs represent a mature technology and are readily available. The work has led to the development of a new type of single-mode VCSEL with a unique combination of characteristics for the benefit of fibre optic RF links. We have also assembled analogue links using VCSELs and high-bandwidth multimode fibres and evaluated their RF transmission characteristics with respect to requirements in different wireless communication systems.

Section 2 presents the design and performance of standard 850 nm oxide-confined VCSELs in terms of impedance, modulation response and bandwidth, intensity noise, and intermodulation distortion and dynamic range, and compares the performance of single and multimode VCSELs. In section 3 we present the performance characteristics of fiber optic RF links using VCSELs and high-bandwidth multimode fibers. Section 4 presents the design and performance of a new high-power single-mode VCSEL which allows for a significant improvement in link gain and noise level. Finally, the summary and conclusions are presented in section 5.
2. High-frequency VCSEL dynamics

Desirable characteristics of a VCSEL (or any laser) used in a directly modulated fibre optic RF link include an efficient transfer of RF power from the signal source to the modulated optical carrier, low relative intensity noise (RIN), low distortion, and high fibre-coupling efficiency [5]. Efficient RF transfer requires a high slope efficiency, a good impedance match (to 50 Ω), and small parasitic RF loss. Low RIN levels and high coupling efficiency suggest the use of a single-mode VCSEL which has no mode partition noise and low beam divergence. Major sources of distortion are the intrinsic non-linearity associated with the relaxation oscillations and spatial hole-burning-induced distortion [11]. This again suggests the use of a single-mode VCSEL which has a high resonance frequency and a strongly clamped carrier density because of the high photon density. All this indicates that the performance under direct high frequency modulation should depend on the modal characteristics of the VCSEL.

We have measured and compared the most important analogue modulation characteristics of single and multimode oxide-confined VCSELs [12]. The VCSELs are GaAs-based, emit at 850 nm, and have a proton implant under the bond pad for reduced parasitic capacitance (figure 1). The bottom n-Al_{0.12}Ga_{0.88}As/Al_{0.90}Ga_{0.10}As mirror has 33 periods and the top p-Al_{0.12}Ga_{0.88}As/Al_{0.90}Ga_{0.10}As mirror has 21 periods. The interfaces between the mirror layers...
are graded to reduce the resistance and the active region contains three GaAs/Al$_{0.20}$Ga$_{0.80}$As quantum wells in a graded AlGaAs composition region for efficient carrier capture. A selectively oxidized Al$_{0.98}$Ga$_{0.02}$As layer, 30 nm thick and positioned just above the active region, provides current and optical confinement. VCSELs with different oxide aperture diameters in the range 2–10 µm were fabricated, with the 2 µm VCSEL being single-mode and the others being multimode.

Representative power and voltage versus current characteristics are shown in figure 2. Emission spectra for the same VCSELs are shown in figure 3. Notable differences between the 2 µm single-mode VCSEL and the 10 µm multimode VCSEL are the lower slope efficiency (0.2 versus 0.35 W A$^{-1}$), the lower maximum power (0.9 versus 4 mW), and the higher differential resistance (200 versus 60 Ω) of the single-mode VCSEL. This is all related to the small oxide aperture which more strongly confines the current and the light, resulting in a higher resistance, and therefore a higher operating temperature, and a higher diffraction loss.

2.1. Impedance characteristics

The frequency-dependent VCSEL impedance ($S_{11}$) was measured at different bias currents using a network analyser (HP8510). Representative results from measurements in the 0.1–10 GHz range are shown in figure 4 along with fits from an equivalent circuit used to extract the bond pad capacitance, the mirror resistance, and the active region resistance and capacitance [12]. While all VCSELs have a parasitic capacitance of 0.9 pF, the single-mode VCSEL has a much larger differential resistance (200 Ω) due to the small current aperture. This clearly creates an

Figure 2. Output power and voltage as a function of current for a VCSEL with an oxide-aperture diameter of (a) 2 µm and (b) 10 µm.
impedance mismatch and additional parasitic RF loss, which reduces the RF transfer efficiency. The multimode VCSELs, with larger apertures and therefore lower resistances (60 $\Omega$ for a 10 $\mu m$ aperture), have a higher RF transfer efficiency.

2.2. Modulation response and bandwidth

The small signal modulation response ($S_{21}$) was measured using the network analyser (HP8510), a 25 GHz photodetector (New Focus 1434), and a 20 GHz amplifier (New Focus 1422) with the VCSEL butt-coupled to a 50 $\mu m$ core multimode fibre. The measured modulation response for the 2 and 10 $\mu m$ VCSELs, at different bias currents and corrected for the frequency response of the detector, are shown in figure 5.

The frequency-dependent modulation response of a semiconductor laser can be described by the following three-pole transfer function [13]:

$$H(f) = \text{const} \left( \frac{f_r^2}{f_r^2 - f^2 + j(\gamma/2\pi)f} \right) \left( \frac{1}{1 + j f/f_p} \right), \quad (1)$$

where the first part, containing two complex-conjugate poles, represents the intrinsic carrier–photon interaction (second-order system) with resonance frequency $f_r$ and damping rate $\gamma$. The
second part, containing a real pole, represents additional extrinsic limitations due to carrier transport and parasitic elements related to the laser structure, where $f_p$ is the cut-off frequency of the low-pass filter characterizing the extrinsic limitation. By fitting (1) to the measured modulation response (also shown in figure 5), the resonance frequency, the damping rate and parasitic cut-off frequency can be extracted for a given VCSEL at a given bias current [14].

From a rate equation analysis it follows that, ideally, the damping rate is proportional to the square of the resonance frequency [13]:

$$\gamma = K f_r^2 + \frac{1}{\chi \tau_n},$$

(2)

where $\tau_n$ is the differential carrier lifetime and $\chi$ a factor that accounts for carrier transport effects. From a plot of the damping rate as a function of the square of the resonance frequency, we can determine the $K$-factor for a given VCSEL. The $K$-factor can then be used to estimate the maximum intrinsic bandwidth (damping limited) in the absence of other limitations [13]:

$$f_{3dB, damping} = \frac{2\pi \sqrt{2}}{K}.$$  

(3)

**Figure 4.** Impedance in the frequency range 0.1–10 GHz for VCSELs with different oxide-aperture diameters: (a) 2 $\mu$m and (b) 10 $\mu$m.
At high bias currents, the resonance frequency may saturate and reach a maximum value of $f_{r,\text{max}}$ because of thermal effects. In the absence of other limitations, the maximum modulation bandwidth (thermally limited) is then [13]

$$f_{3dB,\text{thermal}} = \sqrt{1 + \sqrt{2} f_{r,\text{max}}}. \quad (4)$$

Finally, in the absence of damping and thermal limitations, the maximum modulation bandwidth, limited by parasitics and transport effects, would be [13]

$$f_{3dB,\text{parasitics}} = (2 + \sqrt{3}) f_p. \quad (5)$$

Performing this analysis we find that the modulation bandwidth of the largest multimode VCSEL (10 $\mu$m) is limited to 9 GHz by a combination of damping and parasitic effects, while the modulation bandwidth of the small (2 $\mu$m) single-mode VCSEL is limited to 6 GHz by a considerably higher damping due to strong gain compression as a result of the high photon density.

A laser used in an analogue link should be modulated at a frequency considerably below the resonance frequency since both noise and distortion attain their maximum values at the resonance frequency. A parameter of great importance is therefore the rate at which the resonance frequency increases with current above threshold. From a rate equation analysis we have [14]

$$f_r = D\sqrt{I - I_{th}}, \quad (6)$$

where $I$ the bias current and $I_{th}$ the threshold current. From the modulation response measurements we find that the largest multimode VCSEL (10 $\mu$m) has a $D$-factor of 3 GHz mA$^{-1/2}$.

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**Figure 5.** Small signal modulation response for VCSELs at different bias currents for aperture diameters of (a) 2 $\mu$m and (b) 10 $\mu$m. Also shown are fits to (1).
whereas the small single-mode VCSEL (2 \( \mu \text{m} \)) has a \( D \)-factor as large as 12 GHz mA\(^{-1/2} \). The high value of the \( D \)-factor for the single-mode VCSEL is a result of the small cavity and gain volumes and the high photon density.

Although the single-mode VCSEL is favoured by a high \( D \)-factor, the multimode VCSEL has a modulation response at frequencies below the resonance frequency which is some 10–15 dB higher (figure 5). This is partly due to the better impedance match and the lower parasitic RF loss and partly due to the higher slope efficiency.

2.3. Relative intensity noise

The intrinsic intensity noise of a semiconductor laser is quantified using the relative intensity noise (\( \text{RIN} \)) defined as [13]

\[
\text{RIN} = \frac{\langle \delta P(t)^2 \rangle}{P_0^2}, \quad (7)
\]

where \( P_0 \) is the average power and \( \langle \delta P(t)^2 \rangle \) denotes the mean square power fluctuation. From a small-signal analysis of the rate equations for a single-mode laser, with the driving force being the spontaneous emission, the \( \text{RIN} \) spectrum attains the following frequency dependence [13]:

\[
\text{RIN}(f) = \frac{Af^2 + B}{(f_r^2 - f^2)^2 + (\nu/2\pi)^2 f^2}, \quad (8)
\]

which shows that \( \text{RIN} \) peaks at the resonance frequency.

Intensity noise spectra were measured using an optical receiver (New Focus 1580), followed by a low-noise amplifier (Miteq JS3-00101200-23-5A) and an electrical spectrum analyser (Agilent E4440A). Care was taken to avoid mode-selective coupling and optical feedback by using anti-reflection coated collecting optics with a large numerical aperture.

Intensity noise spectra at different drive currents are shown in figure 6 for the 2 and 10 \( \mu \text{m} \) VCSELs. These spectra contain both the laser \( \text{RIN} \) and the shot noise, with the equivalent shot noise \( \text{RIN} \) given by

\[
\text{RIN}_s(f) = \frac{2q}{I_0} = \frac{2q}{\Re P_0}, \quad (9)
\]

where \( I_0 \) is the dc-photocurrent in the optical receiver and \( \Re \) is the detector responsivity. The equivalent shot noise \( \text{RIN} \) at the highest bias current is indicated by dashed lines in figure 6. At high bias current, the noise of the single-mode VCSEL saturates at the shot noise floor whereas the noise of the multimode VCSEL is higher due to mode competition (mode partition noise), possibly accentuated by some unavoidable mode-selective coupling. Therefore, the single-mode VCSEL has the lowest intensity noise, a clear advantage for analogue links.

2.4. Intermodulation distortion and dynamic range

Non-linearities in the response of the VCSEL cause distortion of the analogue signal. Major sources of distortion are the intrinsic non-linearity associated with the relaxation oscillations and
Figure 6. Intensity noise (sum of $RIN$ and shot noise) spectra for VCSELs at different bias currents for aperture diameters of (a) 2 $\mu$m and (b) 10 $\mu$m.

spatial hole-burning-induced distortion [11]. To illustrate these phenomena, and their frequency dependences, we show in figure 7 the measured and calculated second-order harmonic distortion for a single and a multimode VCSEL at different bias currents. At modulation frequencies near the resonance frequency, the distortion peaks due to the intrinsic non-linearity associated with the relaxation oscillations. At lower frequencies ($<2$ GHz), spatial hole-burning-induced distortion dominates. At intermediate frequencies, the two effects cancel, resulting in a significantly lower distortion. Other effects such as spectral hole burning (accounted for by the gain compression factor) were found (through simulations) to have a small effect on the relative distortion levels. It should also be pointed out that for multimode VCSELs, because the distortion of individual modes can be much higher than for the total output, it is important to avoid mode-selective coupling to the optical fibre to keep the distortion at low levels [11].

Of particular importance for system applications is the third-order intermodulation distortion (IMD3), which shows the same qualitative dependence on the modulation frequency as the harmonic distortion [11]. The IMD3, together with the modulation response and the noise, determines the spurious free dynamic range ($SFDR$), which is the most important quality measure for a laser in analogue systems. A definition of the $SFDR$, as well as other measures of importance such as the input third-order intercept point ($IIP3$) and the output third-order intercept point ($OIP3$), are given in figure 8.
Figure 7. Simulated and measured second-order harmonic distortion as a function of modulation frequency for single-mode and multimode VCSELs at different bias currents. (a) Simulated, single mode; (b) measured, single mode; (c) simulated, multimode and (d) measured, multimode.

Figure 8. Definition of SFDR, IIP3 and OIP3.
The SFDR was measured as a function of modulation frequency and bias current using two-tone measurements. The output from two signal generators (HP8665B), separated in frequency by 1 MHz, were combined and fed to the VCSEL together with the bias current. The output from the VCSEL was coupled into a multimode fibre (again using anti-reflection coated collecting optics with a large numerical aperture) and detected by an optical receiver (New Focus 1580). An electrical spectrum analyser (Agilent E4440A) was used to monitor the power in the fundamental tones, the IMD3s, and the noise level.

Results comparing the single-mode (2 µm) VCSEL and a 6 µm multimode VCSEL (which had the highest SFDR) are shown in figure 9. The SFDR of the multimode VCSEL is in the range 105–110 dB Hz$^{2/3}$ for frequencies between 1 and 5 GHz. The single-mode VCSEL has an SFDR which is 5–10 dB lower. This is mainly due to the lower modulation response. Therefore, because of poor RF transfer efficiency, the low-noise and low-distortion characteristics of the single-mode VCSEL cannot be used to their full advantage.

A detailed description of the dependence of all relevant modulation characteristics on the transverse-mode behaviour can be found in [12].

3. RF links using VCSELs and multimode fibres

To evaluate the full potential of 850 nm VCSELs for cost-effective fibre optic RF links we have assembled links using single and multimode VCSELs, and standard and high-bandwidth
multimode fibres [15]. Important link parameters include the SFDR, the link gain, and the noise figure of the link [5].

The intrinsic link gain is defined as the ratio of the RF power generated in the detector load resistance ($P_{\text{out}}$) to the RF power delivered to the laser ($P_{\text{in}}$). The gain in a directly modulated link, excluding RF loss due to impedance mismatch, is then given by

$$g = \frac{P_{\text{out}}}{P_{\text{in}}} = s_l^2 \eta_l \eta_f T_{\text{fibre}}^2 \eta_{\text{fd}}^2 s_f^2 \frac{R_{\text{load}}}{R_l},$$

where $s_l$ the laser slope efficiency, $\eta_f$ the laser–fibre coupling efficiency, $T_{\text{fibre}}$ the fibre transmission, $\eta_{\text{fd}}$ the fibre–detector coupling efficiency, $\eta_l$ the detector responsivity and $R_{\text{load}}$ and $R_l$ are the detector load resistance and laser resistance, respectively. It follows from (10) that the link gain depends quadratically on the RF transfer efficiency in both the laser ($s_l$) and the detector ($\eta_l$). It also depends quadratically on all optical losses.

The noise figure ($NF$) is a measure of the reduction of the signal-to-noise ratio between the input and the output of the link and is defined as

$$NF = \frac{(S/N)_{\text{in}}}{(S/N)_{\text{out}}}. \quad (11)$$

By definition, the input noise is assumed to be the noise power delivered by a matched resistive load ($kT_0$) held at $T_0 = 290$ K. The $NF$, expressed in dB, then becomes

$$NF = 10 \log \left( \frac{N_{\text{out}}}{kT_0 g} \right), \quad (12)$$

where the output noise contains contributions from laser $RIN$, shot noise and thermal noise. The noise power spectral densities of these components, assuming a lossy link, can expressed as follows:

$$N_{\text{out}, RIN} = I_0^2 RIN R_{\text{load}}, \quad (13)$$

$$N_{\text{out}, \text{shot}} = 2q I_0 R_{\text{load}}, \quad (14)$$

$$N_{\text{out}, \text{thermal}} = kT + \text{additional receiver noise}. \quad (15)$$

The output noise can also be related to the input noise of the link where it is referred to as the equivalent input noise ($EIN$), defined as

$$EIN = \frac{N_{\text{out}}}{g}. \quad (16)$$

Finally, the SFDR is related to the input third-order intercept point ($IIP3$) and the $EIN$ according to

$$SFDR = \frac{2}{3}[IIP3 - EIN - 10 \log(B)], \quad (17)$$

where $B$ is the measurement bandwidth.
Figure 10. SFDR for a complete link as a function of modulation frequency at different VCSEL bias currents.

For the link measurements [15] we have used the small aperture (2 µm) single-mode VCSEL and the 6 µm multimode VCSEL, which had the highest SFDR. We have also used two types of multimode fibres, both being graded index fibres with a core diameter of 50 µm, a numerical aperture of 0.2, and an attenuation of 3 dB km⁻¹ at a wavelength of 850 nm. The standard fibre has a bandwidth-distance product of 400 MHz km at 850 nm, while the corresponding number for the high bandwidth fibre is 2000 MHz km. Fibre lengths range from 1 to 500 m and the VCSELs are butt-coupled to the fibres. The optical receiver is a 12 GHz fibre-coupled receiver with a built-in amplifier (New Focus 1580). The fibre-coupled responsivity is 0.42 AW⁻¹ and the receiver noise was measured to be −171 dBm Hz⁻¹ at 2 GHz. The internal amplification was 31 dB. However, this amplification is not included in the intrinsic link gain.

The measurements show that links with the standard fibre exhibit strong dips in the SFDR and link gain, with corresponding peaks in the NF, at certain fibre-length-dependent frequencies [15]. This is caused by interference between different mode groups with different propagation delay [16]. The high bandwidth fibre, on the other hand, has an index profile optimized for 850 nm, and hence there is a much smaller difference in propagation delay between different mode groups. Therefore, the performance of links with the high bandwidth fibre is superior, with a much smaller frequency dependence.

A comparison between links with single and multimode VCSELs shows that the SFDR for links with the single-mode VCSEL is about 10 dB lower than for links with the multimode VCSEL [15]. This is consistent with the SFDR measurements on the VCSELs presented in section 2.4. Therefore, best performance is achieved for links with the multimode VCSEL and the high-bandwidth multimode fibre. Results for a link with a 500 m long fibre are illustrated in figures 10 and 11, which show the SFDR as a function of frequency at different bias currents and the frequency dependence of the intrinsic link gain and the NF with the VCSEL biased for the highest SFDR, respectively. In the 1–5 GHz range, the SFDR is around 105 dB Hz²/³. The somewhat lower SFDR after 500 m of propagation is due to attenuation in the fibre which accentuates the thermal receiver noise. In the same frequency range, the intrinsic link gain is −30 dB and the link NF is 40 dB.

An analysis using (10), at a frequency of 2 GHz, shows that the major contribution to RF loss (link gain) comes from the limited VCSEL slope efficiency and the impedance mismatch.
and parasitic RF loss, which together amounts to $-20 \text{ dB}$. Using (11)–(16) we have calculated the noise spectral power densities at the link output and the $EIN$ to be

\[
N_{\text{out, } RIN} = -164 \text{ dBm Hz}^{-1}, \quad N_{\text{out, shot}} = -172 \text{ dBm Hz}^{-1},
\]
\[
N_{\text{out, thermal}} = -171 \text{ dBm Hz}^{-1}, \quad EIN = -135 \text{ dBm Hz}^{-1},
\]

showing that laser $RIN$ is the dominating source of noise. The calculated $NF$ using these numbers is 39 dB, in good agreement with the measured $NF$. Finally, using the measured $IIP3$ of +19 dBm, we calculate the $SFDR$ to be 102 dB Hz$^{2/3}$ using (17), which is in good agreement with the measured value of 104 dB Hz$^{2/3}$.

The $SFDR$ for the present link is quite high, satisfying the requirements in a number of applications, including cellular systems for mobile communication and W-LANs [17]–[20]. However, compared with more conventional fibre optic RF links, using edge emitting lasers and single-mode fibres, the link gain is low and the $NF$ is high. This is due to the relatively low RF power transfer efficiency of the VCSEL which decreases the link gain (10) and increases the $NF$ (12).

Finally, we have also measured the influence of lateral VCSEL–fibre misalignment on link performance and found a misalignment tolerance as large as $\pm 12 \mu \text{m}$ for a variation in $SFDR$ and link gain of less than 3 dB for this particular combination of VCSEL and fibre.

4. VCSELs optimized for RF applications

The studies above on the direct high-frequency modulation of VCSELs and on fibre optic RF links using such VCSELs suggest that single-mode VCSELs would be superior to multimode VCSELs if the RF transfer efficiency of the single-mode VCSEL could be improved. We would
then improve the link gain and NF while at the same time benefit from the low-noise and low-distortion characteristics of single-mode VCSELs. In addition, single-mode VCSELs provide the highest fibre coupling efficiency (which is important for the link gain (10)) and problems with mode-selective coupling (which increases noise and distortion when multimode VCSELs are used) are avoided.

The poor RF transfer efficiency of standard single-mode VCSELs (with a small oxide aperture) stems from the large differential resistance which causes a large impedance mismatch and a large parasitic RF loss, and the high diffraction loss which lowers the slope efficiency. In addition, the high operating temperature due to severe Joule heating might further lower the slope efficiency through a reduced internal quantum efficiency. A high operating temperature may also introduce leakage currents which are known to increase distortion [21]. Therefore, a single-mode VCSEL with a large current aperture, and therefore low resistance, should provide improved performance.

We have fabricated such VCSELs by etching a shallow mode filter in the top mirror for fundamental-mode selection in an oxide-confined VCSEL with a relatively large oxide aperture of 6 µm (figure 12) [22]. The VCSEL is based on an ‘inverted’ design with an extra thick top layer for an anti-phase reflection at the semiconductor/air interface. This reduces the overall mirror reflectivity. A thin disk etched in the centre of the top layer locally restores the high reflectivity where the fundamental mode is localized, thereby introducing mode selectivity, resulting in

**Figure 12.** Oxide-confined VCSEL with a shallow mode filter etched in the top mirror for single-mode operation: (a) cross-sectional view and (b) top view.
single fundamental-mode operation over the entire operating range (figure 13). In addition, the epitaxial structure is optimized for high slope efficiency by engineering the doping profile in the top mirror for low internal loss through free carrier absorption. This method only involves a slight modification to standard VCSEL fabrication. The ‘inverted’ design also relaxes the required etch-depth precision compared with the conventional design for mode selection using a shallow surface structure [23, 24].

A unique combination of laser characteristics for the benefit of fibre optic RF links is obtained (figure 13), including low differential resistance (80 Ω), high-slope efficiency (0.8 W A$^{-1}$), low beam divergence (12° FWHM), high output power (6 mW), low RIN ($<-150$ dB Hz$^{-1}$), and high modulation bandwidth (8 GHz). The measured $SFDR$ is 110 dB Hz$^{2/3}$ at 2 GHz and 105 dB Hz$^{2/3}$ at 5 GHz. Link measurements also show that a 10 dB improvement in link gain can be achieved over that obtained for the standard multimode VCSEL [25]. This also improves the link $NF$ by 10 dB since the $NF$ of a lossy link is inversely proportional to the link gain (12).

**Figure 13.** Output power (a) and emission spectra at different bias currents (b) for the high-power single-mode VCSEL.
5. Summary and conclusions

The study shows that fibre optic RF links with 850 nm VCSELs and multimode fibres can provide the performance required in applications such as DAS in cellular systems for mobile communications. Highest performance is obtained for a low resistance, high-power single-mode VCSEL and a high-bandwidth multimode fibre. Performance for a 500 m long link, operating in the 1–5 GHz frequency range, includes an SFDR of 100–105 dB Hz$^{2/3}$, a link gain of $-20$ dB, and a link NF of 30 dB. The use of VCSELs and multimode fibres, allowing for a relatively large misalignment tolerance, should enable the assembly of such links at low cost.

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