Paper

# Vertical cavity surface emitting lasers in radio over fiber applications

Tamás Marozsák and Eszter Udvary

**Abstract — Theoretical and experimental study of using direct modulated vertical cavity surface emitting lasers in radio over fiber applications is presented. The nonlinear distortion and signal to noise ratio are investigated and evaluated in case of short-range multi-carrier transmission. Nonlinear characterization and comparison of the different kind of semiconductor lasers are also presented.**

***Keywords — VCSEL, analog modulation, nonlinear distortion, radio over fiber.***

## 1. Introduction

A modern communication system needs to be flexible, efficient, cheap, and should operate at high data rates. Such a system can use radio links between portable and mobile user equipment such as notebook computers and mobile telephones. This ensures flexibility and convenient services. For providing high capacity and for using the available frequency band efficiently the cell size should be small which requires many radio base stations or radio nodes as called in this paper. These radio nodes can be connected by optical fiber as a relatively cheap and high bandwidth solution. The optical fibers transmit the modulated radio carriers to the radio nodes allowing the radio node to be very simple. The optical fiber may transmit high data rate baseband digital signal as part of the local LAN at the same time.

For such a subcarrier multiplexed optical application great dynamic range and high linearity are required for the optical devices to have good system performance and avoid channel crosstalk. In the last few years the new generation of semiconductor lasers, the vertical cavity surface emitting lasers (VCSEL) proved to be competitive to the conventional, high performance edge emitting communication lasers [1]. In this paper some theoretical system considerations and the comparison of the different laser types based on spurious free dynamic range measurements are presented.

## 2. Signal to noise ratio

The figure of merit in a radio communication system is the signal to noise ratio ($S/N$) in the receiver. Because the radio nodes (RN) are fed by an optical link in the above-mentioned radio over fiber system, the effect of the optical link should be considered. Figure 1 shows a simplified connection between a user and a radio node. The RN receives the optical signal by a high-speed photodetector (PD), it is amplified and transmitted by the antenna. In uplink direction the radio signal from the user is amplified by a low noise receiver, which directly modulates the laser source (LD).

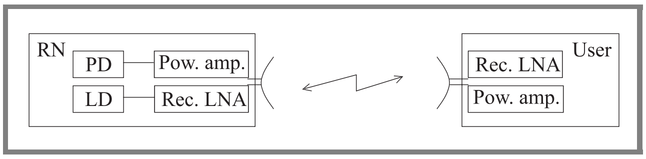


***Fig. 1.*** Considering optical link noise in radio link.

The power amplifier in the RN will not degrade the signal to noise ratio coming from the PD. Because the signal and the transmitted noise are both attenuated in the radio channel, probably the receiver low noise amplifier (LNA) will determine the noise and hence, the $S/N$. In uplink direction the received signal is amplified by the RN LNA. The noise level after the LNA is probably higher than the relative intensity noise of the laser, which means that the noise of the optical link has no effect on the overall $S/N$, it will be determined by the radio link. More precisely this is the case if the $S/N$ of the optical link is higher than the $S/N$ of the radio link. To estimate the achievable signal to noise ratio in an optical link the nonlinearity and the noise of the optical link should be considered.

The laser relative intensity noise ($RIN$) and the receiver noise are the main noise sources in an optical link. It is a good assumption that the noise is determined by the laser if the optical attenuation is not high and this way the detected laser noise power is higher than the thermal noise of the receiver (the shot noise is usually smaller).

This is true if the fiber attenuation is less then

$$a = \frac{I_{ne}}{P_{LD} \cdot R_{PD} \cdot \sqrt{RIN}}, \qquad (1)$$

where $I_{ne}$ is the equivalent noise current density of the optical receiver, $RIN$ is the laser intensity noise, $P_{LD}$ is the output power of the laser, $R_{PD}$ is the photodiode responsivity. This gives $a = 10$ dB maximum fiber attenuation if $P_{LD} = 1$ mW, $RIN = 10^{-14}$ 1/Hz, $R_{PD} = 1$ A/W and $I_{ne} = 10$ pA/Hz$^{1/2}$ which are practical device values. 10 dB attenuation is more than 30 km optical fiber, which is usually more than the distance range of microwave analog fiber optic links. This yields that the laser noise will determine the optical link performance.

The frequency dependence of the $RIN$ can be rather high, especially when the optical back-reflection (BR) into the laser is high. Typical measured $RIN$ spectra can be seen in Fig. 2 where a Ø14 $\mu$m multimode 850 nm VCSEL was measured at different bias currents. Above 5 mA bias the measurement was limited by the measurement setup. The highest relaxation oscillation frequency was around 7 GHz when 10 mA bias was applied than the optical power in the multimode fiber was 2 mW.

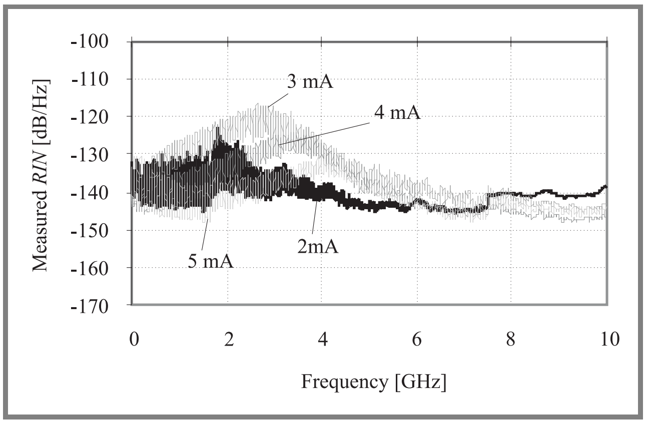


***Fig. 2.*** Measured VCSEL relative intensity noise. Ripples caused by optical reflection.

From Fig. 2 it can be seen that $RIN = -140$ dB/Hz in average. Applying $m = 25\%$ modulation depth, which is a practical value with direct modulation, the $S/N$ of the optical link:

$$\frac{\frac{1}{2}m^2}{RIN} = 125\frac{\text{dB}}{\text{Hz}}. \tag{2}$$

This is usually much higher than the signal to noise ratio in radio links, but it must be noted, that linearity was not considered here ($m$ should be lower if good linearity is required).

## 3. Nonlinear distortion

Linearity is especially important in subcarrier multiplexed systems. As the number of carriers increases the linearity problem become more and more serious because many odd (mainly third) order mixing products appear in the used band. The main source of intermodulation distortion in optical links is always the optical transmitter.

The figure of merit when the nonlinearity is investigated together with noise is the spurious free dynamic range ($SFDR$) defined as [2]:

$$SFDR = \frac{P_{in}(P_T = P_{noise})}{P_{in}(P_1 = P_{noise})} = \left[\frac{IP_3}{P_{noise}}\right]^{\frac{2}{3}}, \tag{3}$$

where $P_1$ and $P_T$ is the power of the detected fundamental and the third order mixing product, respectively, $IP_3$ is the third harmonic intercept point, $P_{noise}$ is the detected noise power. This number is good figure of merit in performance characterization of an optical transmitter. Figure 3 compares the DFB, Fabry-Perot and VCSEL lasers in their $SFDR$ measured as a function of the frequency and modulating signal power. The lasers were biased to 1 mW optical power. The curves show that the VCSEL exhibit the lowest $SFDR$ and its curve is not that smooth as the others. This is mainly because the VCSEL was operated at 850 nm and the photodetector for that wavelength had high optical reflection. Still, the measured $SFDR$ make this laser suitable for radio over fiber applications.

It can be seen that the $SFDR$ decreases as the frequency increases. This is because the $IP_3$ decreases as the frequency approaches the laser relaxation oscillation frequency. It should be also noted that the $SFDR$ should not change with the input power, but when $P_{gen}$ is high the power of the higher order mixing products starts to be in the range of the main signal and the linear and cubic growth is not fulfilled for the fundamental and third harmonic mixing products respectively.

When the laser simultaneously transmits data in the baseband and on radio channels at RF as this possibility was mentioned in Section I, the second order nonlinearity also gets an important role. The baseband signal is mixed with the RF carriers causing distortions. This is shown in Fig. 4, where the laser was modulated with two RF carriers at 2 GHz (Fig. 4a) and than a 500 kHz baseband signal was added to them (Fig. 4b).

In Fig. 4 the laser was biased to 0.8 mW optical power in fiber, the modulation depth $m_{\text{BB}} = 2.7\%$ was for the base band and $m_{\text{RF}} = 11.4\%$ was for the RF signal. Increasing the laser power to 1.2 mW, and hence decreasing the modulation depths, the 3rd order product improved 15 dB, while the second order 9 dB. This yields that very low modulation depth has to be used to avoid distortions to degrade BER seriously. This could be avoided by up-converting the baseband signal into the RF also.

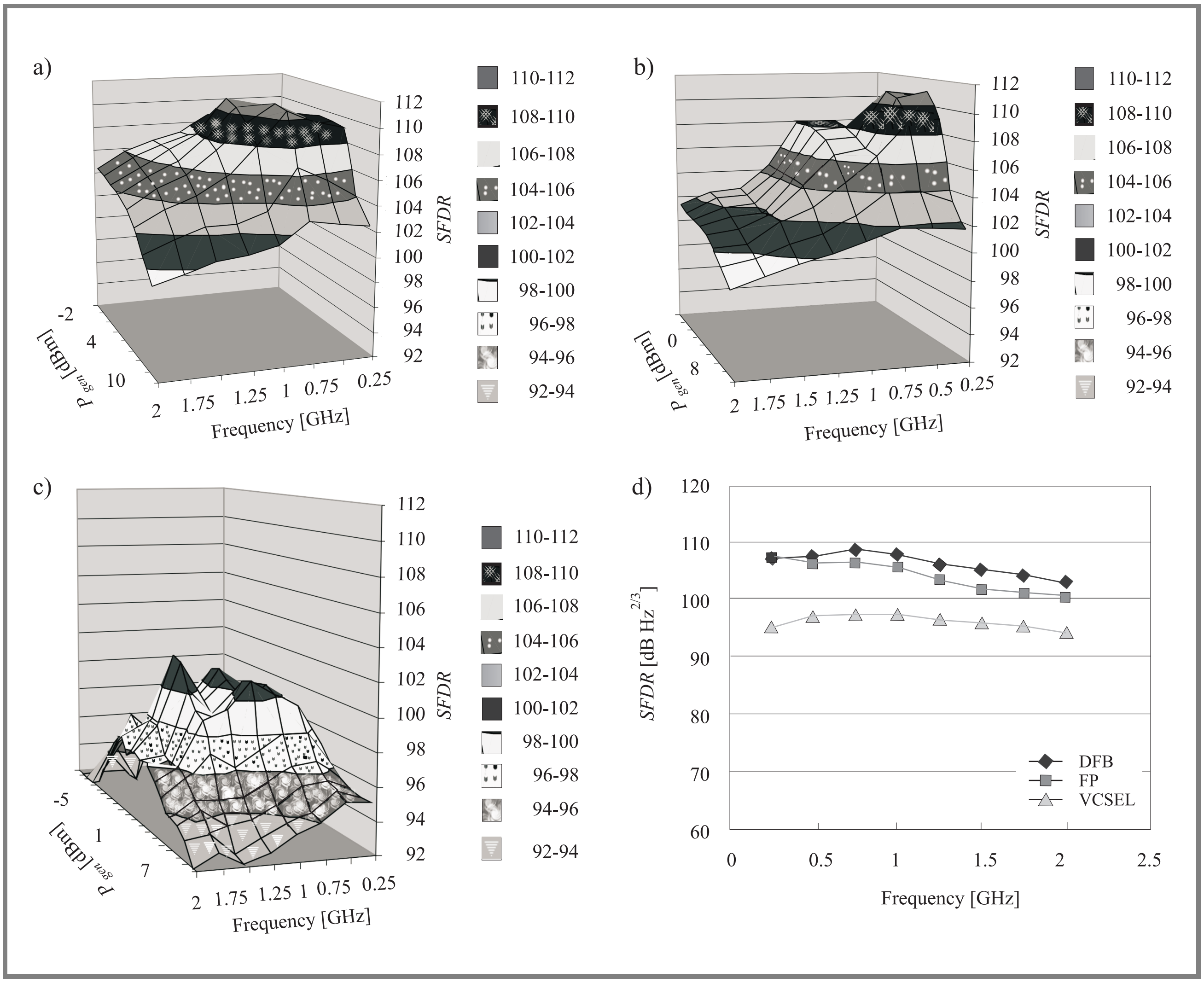


*Fig. 3.* *SFDR* versus frequency and modulating power for DFB (a), FP (b) and VCSEL (c) lasers. Comparison of *SFDR* as a function of the frequency for different laser types (d).

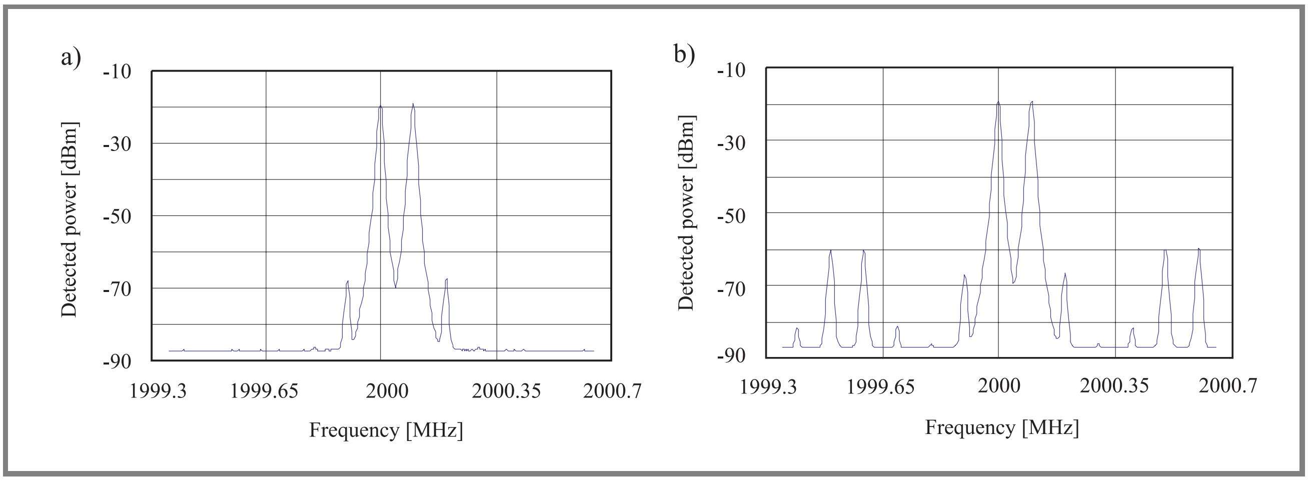


*Fig. 4.* Two tone intermodulation measurement (a) when a baseband signal was also added (b).

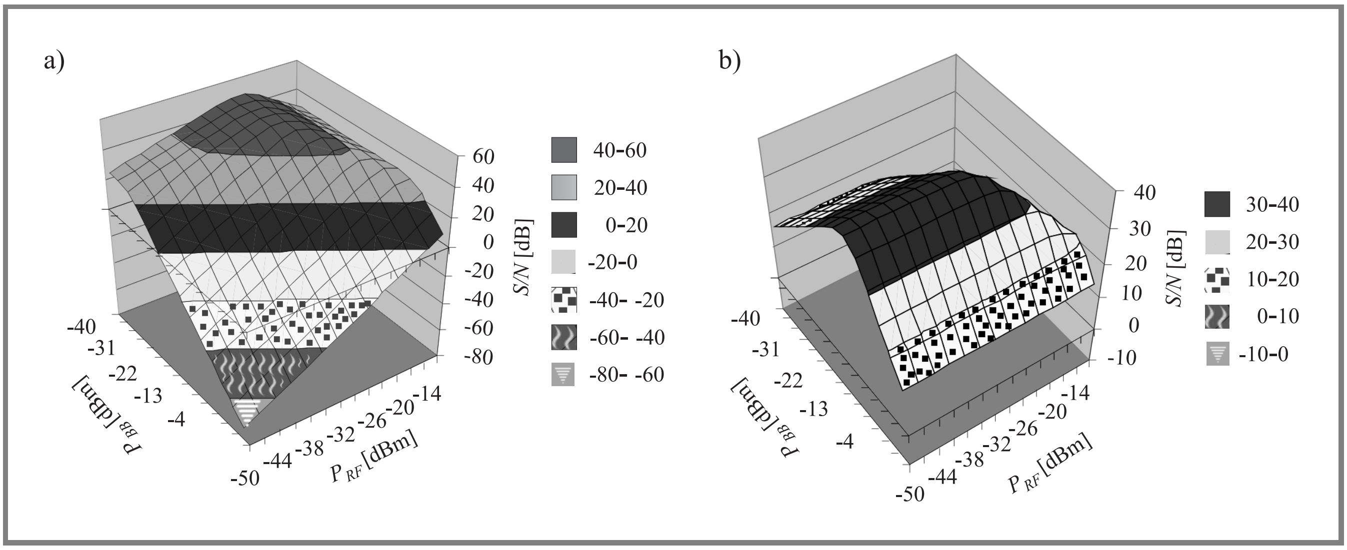


***Fig. 5.*** Calculated signal to noise ratio in a radio channel (a) and in the baseband (b) as a function of modulating power in the baseband ($P_{BB}$) and in the radio band ($P_{RF}$).

## 4. System evaluation

The system described in the first section was evaluated by approximate calculations. The achievable signal to noise ratio was determined for the baseband signal and for a radio channel in the RF band. In the calculation the second and third order frequency conversions were considered. 10 equally spaced radio channels were supposed having 1 MHz modulation bandwidth each. The bandwidth of the baseband digital signal was 100 MHz representing a relatively high bit rate local area network. The parameters are summarized in Table 1. The $IP_2$, $IP_3$, $RIN$ and slope efficiency parameters of the laser source are typical values coming from the measurements.

Table 1
Calculation parameters

| Parametr | Value |
|---|---|
| Optical power | 1 mW |
| *RIN* | −135 dB/Hz |
| Slope efficiency of laser source | 0.3 W/A |
| $IP_3$ of laser source | −5 dBm |
| $IP_2$ of laser source | 15 dBm |
| Photodetector responsivity | 1 A/W |
| System impedance | 50 Ω |
| Baseband bandwidth | 100 MHz |
| RF bandwidth (1 channel) | 1 MHz |
| Number of RF channels | 10 |

The surface in Fig. 5a shows that if $P_{BB} > -19$ dBm the radio channel $S/N$ start to decrease quickly and the same is true for the baseband if $P_{RF} > -20$ dBm (Fig. 5b). Choosing $P_{BB} = -22$ dBm and $P_{RF} = -20$ dBm seems to be good compromise, in that case $S/N_{RF} = 41$ dB, $S/N_{BB} = 21$ dB which are very good values.

## 5. Conclusion

The vertical cavity surface emitting lasers were compared to the popular FP and DFB lasers based on nonlinear dynamic measurements. Its spurious free dynamic range was less than the other candidates but the 95 dB Hz$^{2/3}$ value, measured in higher optical reflection environment, is still appropriate for radio over fiber applications. The measured values were used in a simple system performance calculation where radio carriers and digital signal in the baseband were transmitted at the same time. It was proved that high signal to noise ratio can be achieved with these lasers.

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**Tamás Marozsák** received the M.Sc. degree in electrical engineering from the Technical University of Budapest (TUB), Hungary in 1995. Than became Ph.D. student at Department of Microwave Telecommunications in the field of optical communication. His main interest is microwave photonics, the application and modeling of semiconductor lasers, especially vertical cavity surface emitting lasers. He is author or co-author more than 30 technical papers.
e-mail: marozsak@mht.bme.hu
Department of Microwave Telecommunications
Budapest University of Technology and Economics
1111 Budapest, Goldmann Gy. ter 3
Hungary

**Eszter Udvary** received the M.Sc. degree in electrical engineering from the Technical University of Budapest (TUB), Hungary in 1997. Her M.Sc. thesis was on the design, fabrication and testing of microwave oscillators. Later she began Ph.D. study at the TUB, Department of Microwave Telecommunications. Her research interest includes optical and microwave communication systems, optical and microwave interactions and applications of special electro-optical devices. Her present field of interest is the application of semiconductor optical amplifier (SOA) in optical systems as amplifier, modulator and detector. She published more than 20 technical papers in these fields. She was awarded the Nokia MICROCOLL'99 young researcher conference prize and the URSI Young Scientist Award 2002.
e-mail: eszter.udvary@mht.bme.hu
Department of Microwave Telecommunications
Budapest University of Technology and Economics
1111 Budapest, Goldmann Gy. ter 3
Hungary