Test methods for VCSEL characterization

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Introduction

• Different characterization setups have been implemented directed to measure critical transmitter parameters that influence in the communication channel capacity and reliability of the device:
  • LIV: threshold current, L-I characteristics (slope efficiency), V-I forward voltage drop
  • AC: extrinsic and intrinsic responses, input impedance
  • RIN: noise as a function of bias current and ER

• This contribution explains the test setups and methods used in the characterization of VCSEL devices from several vendors

• Vendors that have kindly contributed with VCSEL samples:
  • TRUMPF
  • VIS
  • II-VI
  • LUMENTUM
  • TrueLight
1. Amphenol SVmicrowave SF1521-60115, 2.92mm female solderless LiteTouch PCB Connector, 2 Hole (CPW / Microstrip)
   • Coaxial to CPWG transition used to connect the coax cable to the PCB where the VCSEL is assembled
2. Marki Microwave BTN-0040 bias tee (40 kHz to 40 GHz)
   • Used to combine bias current with RF signal from VNA or AWG
3. Minicircuits TMP40-3FT-KMKM+, temperature stable 2.92mm cable, 40.0 GHz
   • Used to connect bias tee output to the DUT
4. Minicircuits BW-K10-2W44+, 10 dB fixed attenuator, DC - 40 GHz, 50 Ohm
   • Used to connect the optical receivers to the VNA
5. Newport 1484-A-50 fiber-optic multimode receiver, 800-865nm GaAs detector, 22 GHz, FC/PC
   • Used for S21 response measurement with VNA
   • Calibration provided by the vendor for response de-embedding
6. Newport 1414-50 fiber-optic detector, 850-1630 nm, 25 GHz, FC 50 µm Multimode
   • Used for S21 response measurement with VNA for wavelengths > 850 nm
   • Calibration provided the vendor for response de-embedding
7. Keysight E5080B ENA Vector Network Analyzer
   • S21 magnitude response
   • Z11 real/imag reflect response
8. Keysight N4433A ECal: microwave electronic calibration unit, 300 kHz to 20 GHz
Equipment & Software

9. Keysight B2901A Precision Source/Measure Unit
   • Bias current to VCSEL
   • Voltage drop measurement (V-I curve)

10. Optokon OFT-820
    • Absolute optical power, calibrated for 850 nm

11. Thorlabs FP1000URT 1 mm core multi-mode SI 0.50 NA glass fiber with Ø5.0 mm stainless steel tubing FT05SS
    • Used to collect full optical radiation from VCSEL (L-I curve)

12. SEIKOH GIKEN 7100142-211-1002 APC to PC, MM, SX, OM3, 3mm, 2 meters
    • Used to connect the DUT to the measurement equipments: O/E converters and DCA
    • APC is used in the DUT side to reduce back reflection effect in the RIN and AC response

13. Keysight M8195A 65 GSa/s, 25 GHz, Arbitrary Waveform Generator
    • Used to generate time-domain RF signal that drives the VCSEL
    • Capability of real-time digital signal processing with 8 bits DAC
    • Used to provide symbol clock to DCA

14. Keysight N1092C DCA-M Sampling Oscilloscope (one optical and two electrical channels)
    • Used to make the time-domain characterization with periodic arbitrary signal generated by VCSEL
    • Background noise calibrated for RIN measurement

15. Keysight N1010A FlexDCA Sampling Oscilloscope Software R&D software package

16. Matlab 2019b:
    • Test automation
    • Signal processing
    • Model extraction
Equipment & Software

AC characterization

Time-domain characterization

Thermal chamber

(7) VNA

(2) bias-tee

(5 or 6) O/E

(9) SMU

(9) SMU

(13) AWG

(14) DCA
VCSEL electrical connection

VCSEL

TOP

CPWG

2

BOTTOM

Thermo-couple attachment point

Rogers dielectric
Optical coupling

- VCSEL samples are mounted on a PCB specifically designed for the frequency range used in the characterization (DC ~ 20GHz).

- Therefore, the optical coupling system (VCSEL to Fiber) has been designed considering the mechanical characteristics of the PCB, in addition:
  - it is able to operate in a temperature range of -40 to 125°C. The temperature is controlled with a thermo-stream that pumps dry air into a small chamber (about 35x20x15cm LxWxH).
  - it is mechanically stable to avoid deviations during the thermal cycles.
  - it allows adjustment in the XY plane (parallel to the PCB) to correct the positioning tolerances of the VCSEL.

- Scheme:
  - SSP05 mount is used to attach the lenses and the fiber to the PCB. This mount allows a manual adjustment of 1 mm range in the XY plane.
  - Different spacers are used to adjust the working distance in steps of 50 um (WD is distance between the VCSEL and the first lens):
    - Misumi WASHER: WSX-ST3W-M4X7-0.5: 500 um thickness
    - Misumi SHIMS: PCIMRS4-7-0.05: 50um thickness
  - First lens is A397TM-B: f = 11.0 mm, NA = 0.3, Mounted Rochester Aspheric Lens, AR: 650 - 1050 nm.
  - Second lens is F220FC-850-B: f = 11.12 mm, NA = 0.25 FC/PC Fiber Collimation Pkg with AR: 650 - 1050 nm.
Optical coupling

- SSP05 Mount
- Fiber (APC)
- F220FC-850-B
- A397TM-B
- VCSEL
- PCB
- SF1521-60115
- Spacers to adjust WD
Optical coupling

- Performance of the optical system has been simulated using ray tracing software
  - Simulation is done considering the VCSEL is a perfect point with NA=0.3 and wavelength 850 nm.
  - Spot size in the fiber is less than 1 um, which means the optical system is diffraction limited.
  - This is the best focus, which is obtained with a working distance (WD) of 9.73 mm
Optical coupling

- The maximum reflection occurs when the spot size at the fiber end face is minimum.
  - This occurs at a working distance (WD) of 9.73 mm.
- If we generate a defocus by moving the WD, it is possible to reduce the Back-Reflections.
  - With a variation in the WD of 75um it would be possible to reduce the reflected power by approximately 10dB, while maintaining coupling IL.
- However, working outside the optimum WD may cause loss of tolerances which can make difficult the optical alignment and reduce the stability during thermal cycling.
- Spacers are used to adjust the WD experimentally reducing the back reflections effect in AC response and RIN.
• Bias tee DC resistance is characterized: $R_{\text{Bias-tee}} = 6$ Ohm (constant for the bias currents range)

• Optical power and forward voltage drop are measured in the following conditions:
  • $I_{\text{bias}} = 0.02$ to 2 mA in steps of 0.02 mA, and from 2.2 to 10 mA in steps of 0.2 mA.
  • $T_{BS} = -40, 0, 25, 85, 105, 125$ °C

• Responsitivity of the optical power meter is corrected with actual wavelength of the VCSEL of data-sheet
Test method — AC

- 1-port calibration setup
- Z11 (reflect, real/imag) measurement
- Response calibration setup
- |S21| measurement
Test method — AC

- $S_{21}^{\text{MEAS}}$ (magnitude) and $Z_{11}^{\text{MEAS}}$ (real/imag) are measured with the following configuration:
  - 2001 points linear sweep from 1 MHz to 20 GHz
  - Power -10 dBm
  - IF BW 40 kHz
  - $I_{\text{bias}} = 1$ to 10 mA in steps of 0.5 mA
  - $T_{\text{BS}} = -40, 0, 25, 85, 105, 125 \degree C$

- $Z_{11}^{\text{VCSEL+WB}}$ is calculated from $Z_{11}^{\text{MEAS}}$ and $S_{xy}^{\text{PCB}}$
  - $S_{xy}^{\text{PCB}}$ are $S_{11}^{\text{PCB}}, S_{22}^{\text{PCB}}, S_{21}^{\text{PCB}} = S_{12}^{\text{PCB}}$, of the PCB + coax connector, obtained by OSL calibration, where VCSEL is replaced by open, short and reference impedance load
  - $Z_{11}^{\text{VCSEL+WB}}$ is the Z11 of VCSEL including wire bonding
  - $R_{S}$ (extrinsic series resistance), $R_{J}$ (extrinsic junction resistance) and $f_{P}$ (extrinsic response pole) are calculated by MMSE function fitting of real part of $Z_{11}^{\text{VCSEL+WB}}$

- $H_{VI}$ is the transfer function from voltage signal in the calibration plane to current entering the VCSEL

- $H_{OE}$ magnitude transfer function of the optical to electrical high speed converter is provided by vendor for each unit used (1484-A-50 and 1414-50)

- $H_{\text{VCSEL-INT}}$ intrinsic VCSEL response is calculated from $S_{21}^{\text{MEAS}}, H_{OE}, H_{VI}$, and $f_{P}$

- $f_{r}$ (resonance frequency) and $\gamma$ (damping rate) are MMSE fitted to $H_{\text{VCSEL-INT}}$
Test method — AC

• Equations used in the de-embedding process and the parameters identification:

\[
S_{11\text{ MEAS}} = \frac{Z_{11\text{ MEAS}} - Zo}{Z_{11\text{ MEAS}} + Zo}
\]

\[
S_{11\text{ VCSEL+WB}} = \frac{S_{11\text{ MEAS}} - S_{11\text{ PCB}}}{S_{12\text{ PCB}} \cdot S_{21\text{ PCB}} + S_{22\text{ PCB}} \cdot (S_{11\text{ MEAS}} - S_{11\text{ PCB}})}
\]

\[
Z_{11\text{ VCSEL+WB}} = Zo \cdot \frac{1+S_{11\text{ VCSEL+WB}}}{1-S_{11\text{ VCSEL+WB}}}; \quad \Re\left(Z_{11\text{ VCSEL+WB}}\right) = R_s + \frac{R_J}{1 + \left(\frac{f_r}{f_p}\right)^2};
\]

\[
H_{V} = \frac{S_{21\text{ PCB}} \cdot (1+S_{11\text{ VCSEL+WB}})}{1-S_{22\text{ PCB}} \cdot S_{11\text{ VCSEL+WB}} \cdot Z_{11\text{ VCSEL+WB}}} \cdot \frac{1}{Z_{11\text{ VCSEL+WB}}}
\]

\[
H_{\text{VCSEL-EXT}} = \frac{1}{1 + j \frac{f_r}{f_p}}; \quad H_{\text{VCSEL}} = H_{\text{VCSEL-EXT}} \cdot H_{\text{VCSEL-INT}}
\]

\[
|H_{\text{VCSEL-INT}}| = \left|\frac{S_{21\text{ MEAS}}}{H_{OE} \cdot H_{V} \cdot H_{\text{VCSEL-EXT}}}\right|
\]

\[
H_{\text{VCSEL-INT}} = C \cdot \frac{f_r^2}{f_r^2 - f^2 + j \frac{f}{2\pi} \gamma}
\]

• Small signal AC VCSEL response follows the model shown in several references, like [1], [2] and [3]
Test method — RIN

- Relative Intensity Noise (RIN) is measured in the following conditions:
  - $I_{\text{BIAS}} - I_{\text{TH}}$: from 1.5 to 6 mA in steps of 0.5 mA
  - ER: from 3 to 6 dB in steps of 1 dB
  - $T_{BS}$: -40, 0, 25, 85, 105, 125 °C
- Square signal pattern is used to separate the noise of ISI caused by VCSEL band limited response
Test method — RIN

- AWG generates a clock signal of 1.344 GHz in both ports 1 and 2
  - This is equivalent to transmit 10 \{0\} symbols followed by 10 \{1\} symbols continually with the transmitted symbols timed from a symbol clock of 26.88 GBd

- AWG port 2 amplitude is configured to provide 500 mVpp after response compensation

- AWG port 1 amplitude is adaptively configured to get a target ER measured by the DCA after response compensation

- DCA is configured as follows:
  - SIRC reference filter in channel A of 20.2 GHz (Bessel 4th order)
  - Trigger source: clock in
  - Trigger mode: pattern lock
  - Signal type: clock
  - Pattern length: 1
  - Trigger divide ratio: 1:1
  - Symbol rate: 1.344 GBd
  - Automatic number of samples per UI
  - RIN: OMA mode, dB/Hz units, per IEEE 802.3 definition
  - RN compensation is carried out based on noise histogram sigma characterized in dark input
Test method — RIN

- **RIN_{OMA} definition:**

\[
RIN_{OMA} = 10 \cdot \log \left( \frac{(RN_{\text{one}} + RN_{\text{zero}})^2}{OMA^2 \cdot BW_N} \right) \text{ dB/Hz}
\]

- **RN_{one/zero}:** standard deviation of noise measured in level 1/0 (in Watts)

- **OMA:** optical modulation amplitude (in Watts)

- **BW_N:** noise equivalent bandwidth (in Hz)

  - \( BW_N = 1.04 \cdot BW \), for a 4th order Bessel filter

- Noise variance depends on signal intensity
References


• [3] Seyed Ehsan Hashemi, “Relative Intensity Noise (RIN) in High-Speed VCSELs for Short Reach Communication”, Master of Science Thesis in Photonics Engineering, Chalmers University of Technology