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

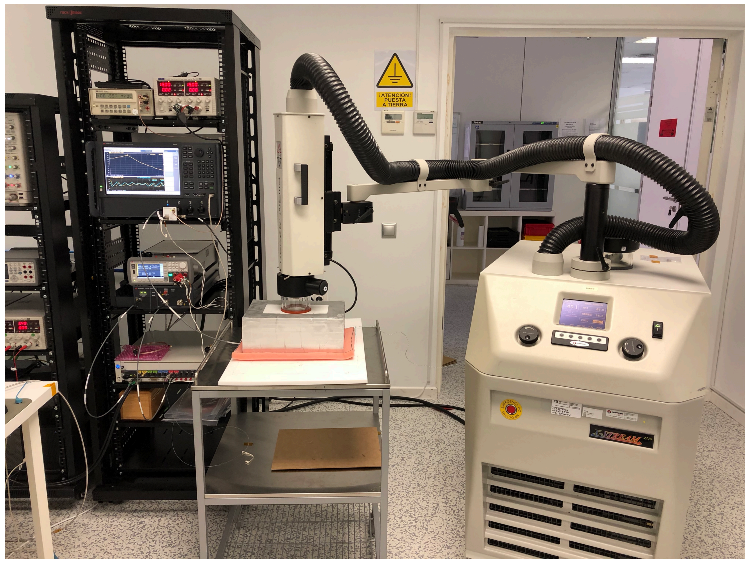
Equipment & Software

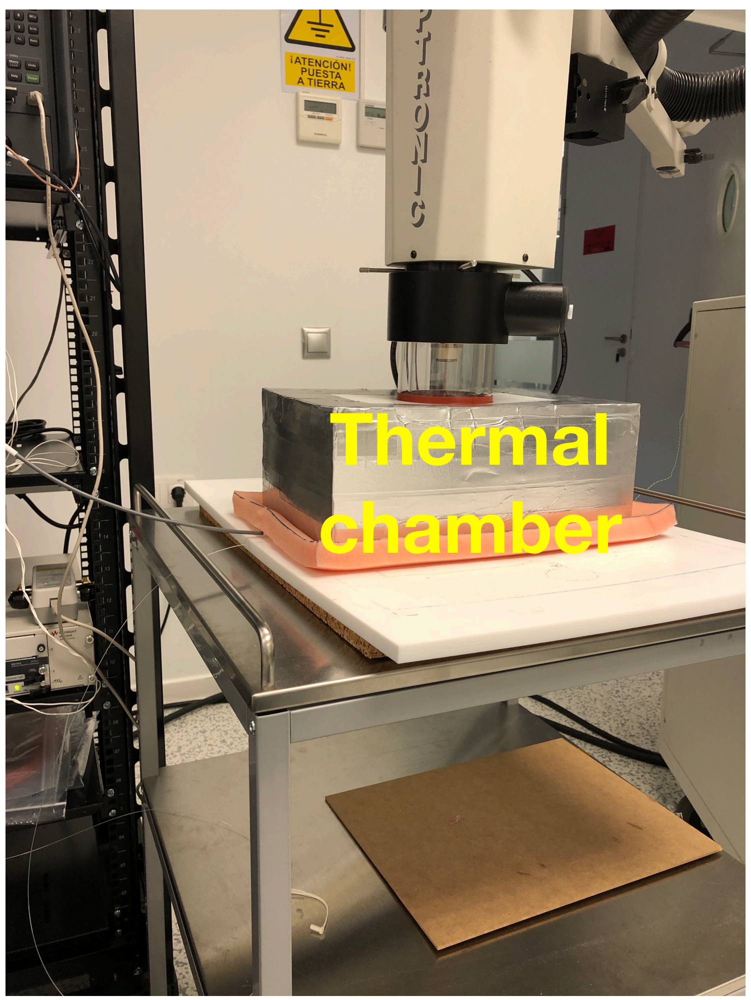
1. Amphenol SVmicrowave SF1521-60115, 2.92mm female solderless LiteTouch PCB Connector, 2 Hole (CPW / Microstrip)
   - Coaxial to CPWG transition used to connect the coax cable to the PCB where the VCSEL is assembled
2. Marki Microwave BTN-0040 bias tee (40 kHz to 40 GHz)
   - Used to combine bias current 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

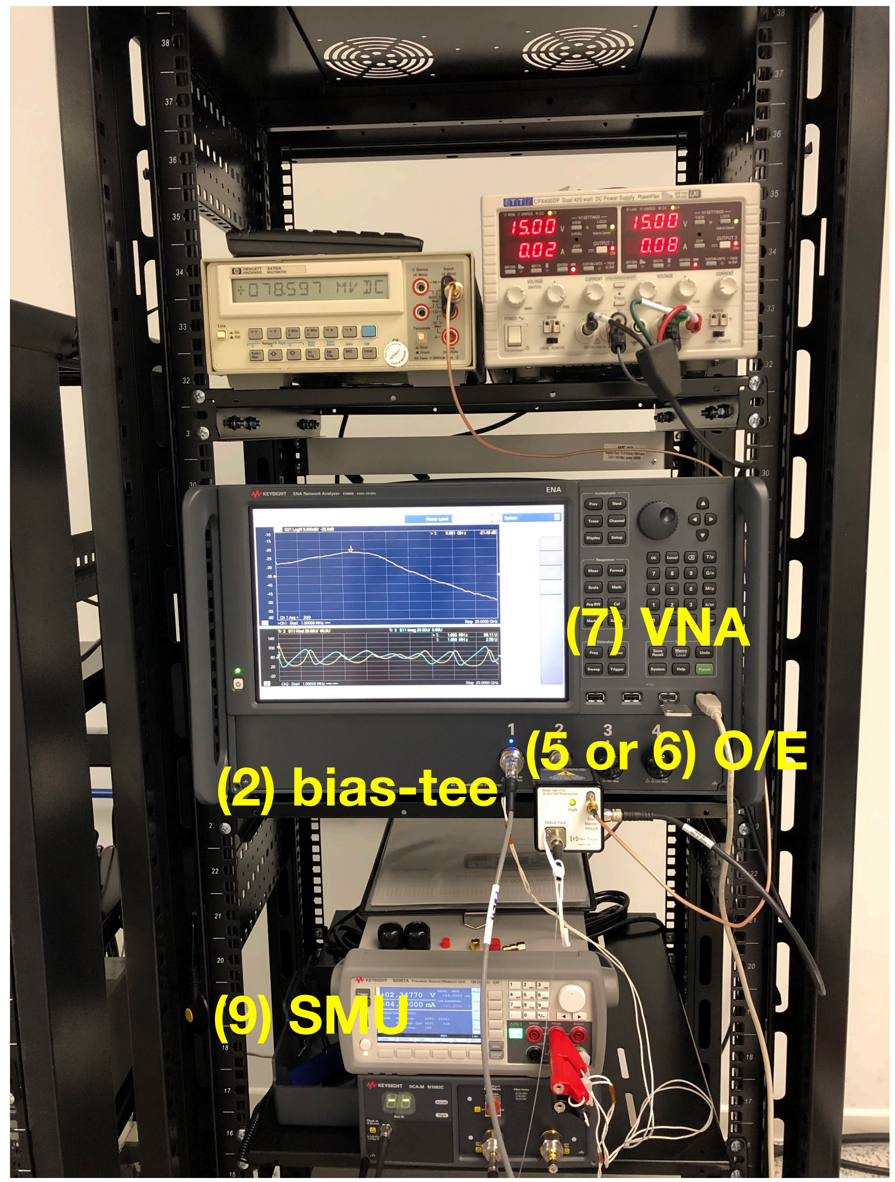
9. Keysight B2901A Precision Source/Measure Unit
    - Bias current to VCSEL
    - Voltage drop measurement (V-I curve)
10. Optokon OFT-820
    - Absolute optical power, calibrated for 850 nm
11. Thorlabs FP1000URT 1 mm core multi-mode SI 0.50 NA glass fiber with Ø5.0 mm stainless steel tubing FT05SS
    - 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

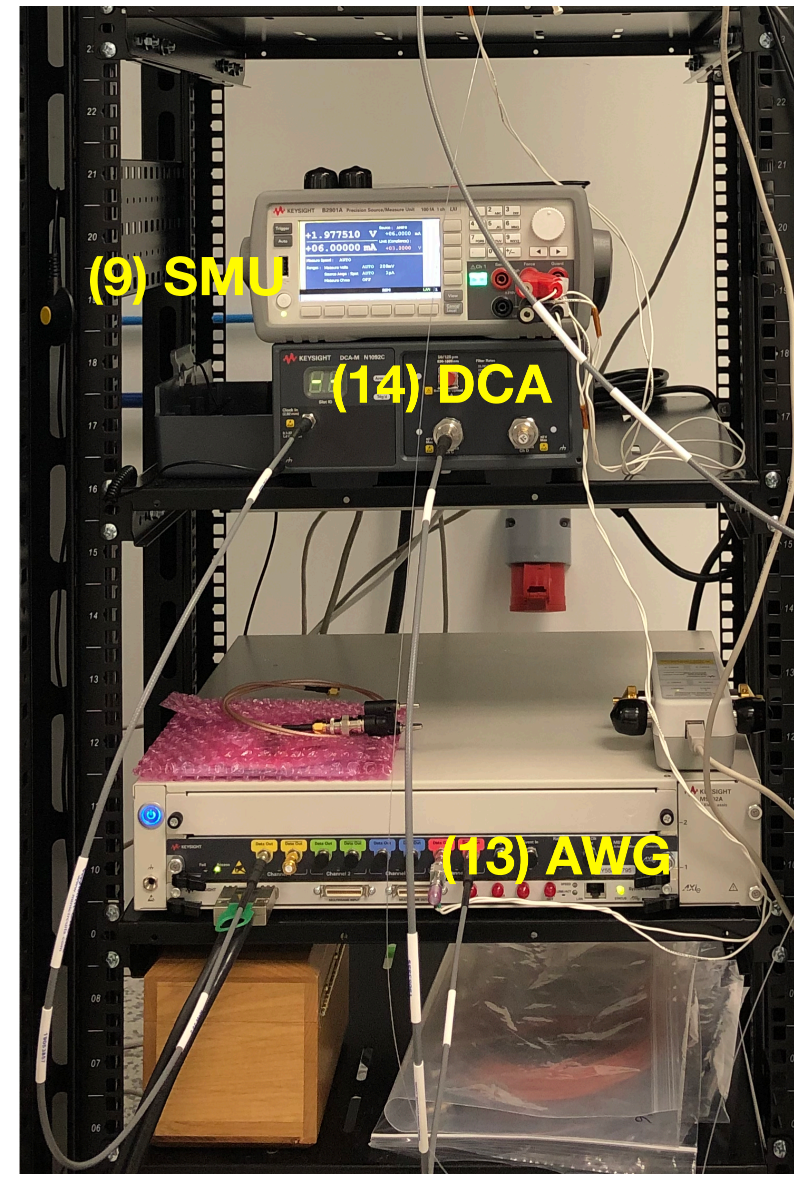




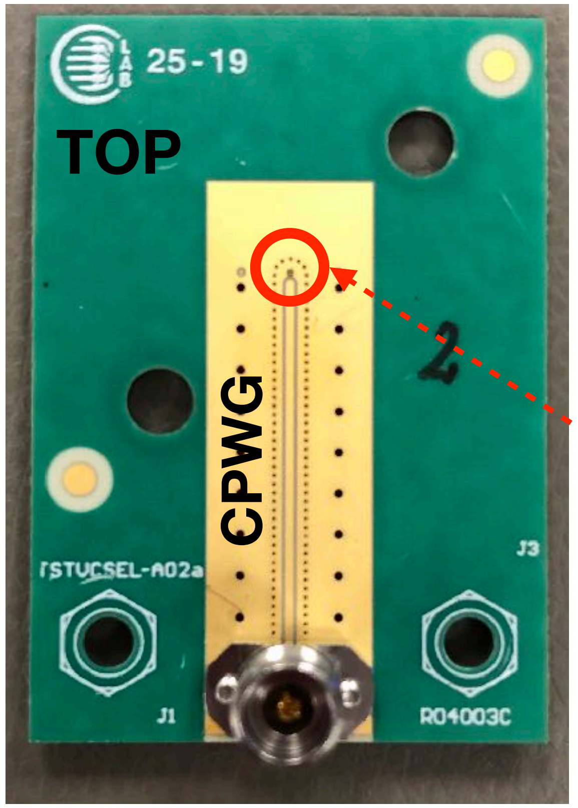
AC characterization



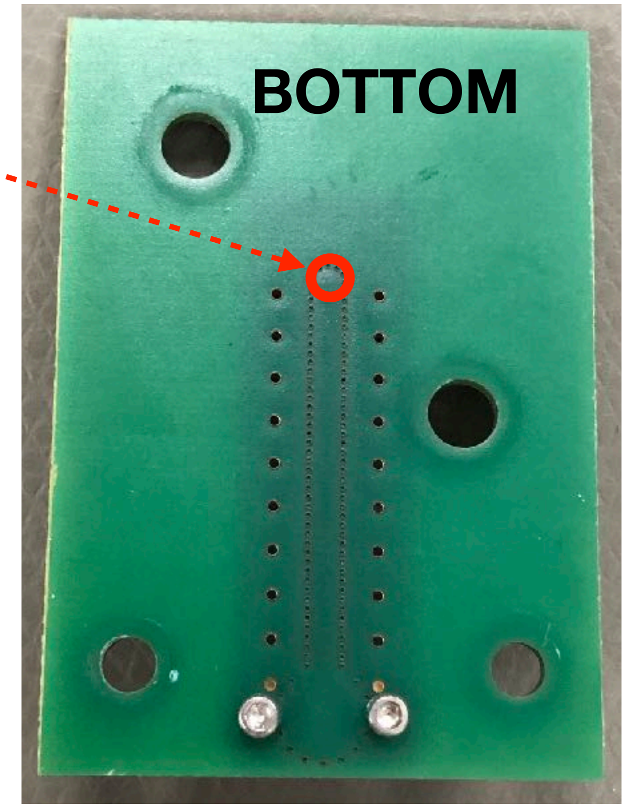
Time-domain characterization



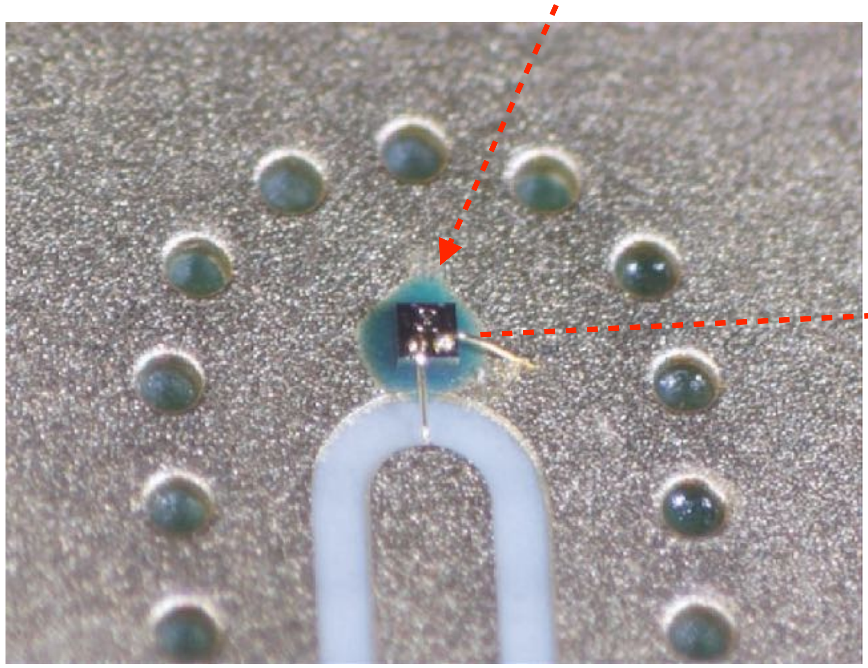
VCSEL electrical connection

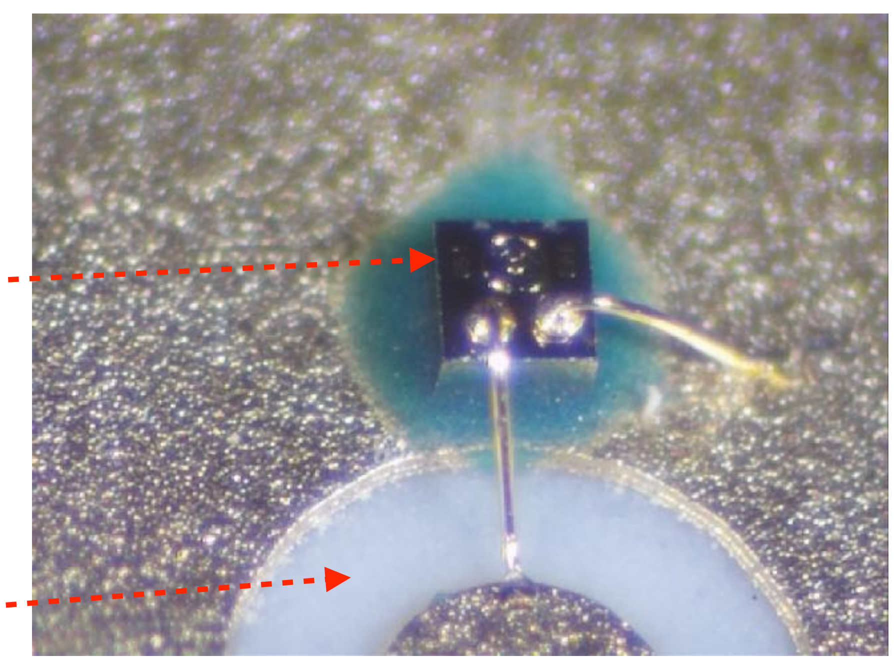


Thermo-couple
attachment point



VCSEL



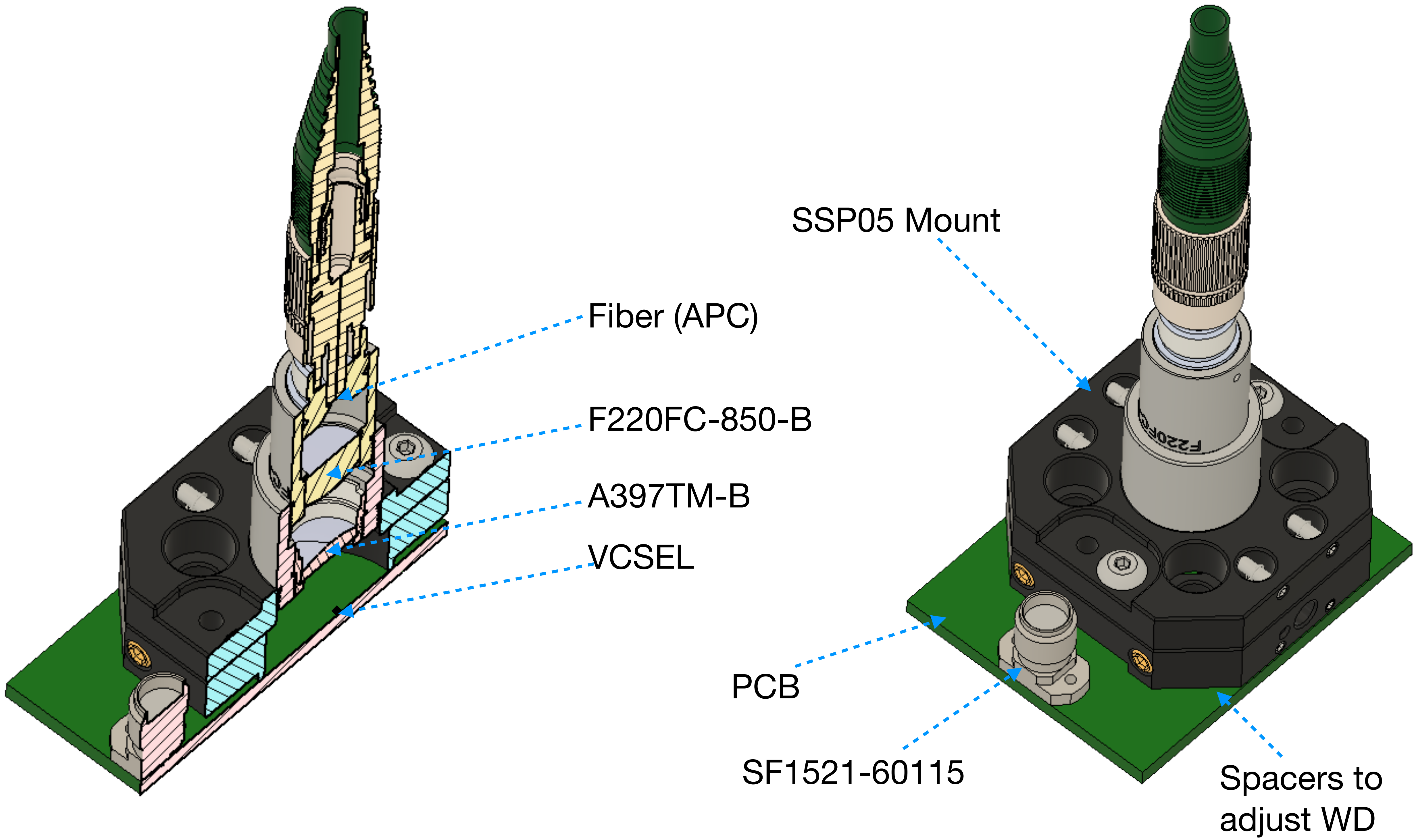


Rogers dielectric

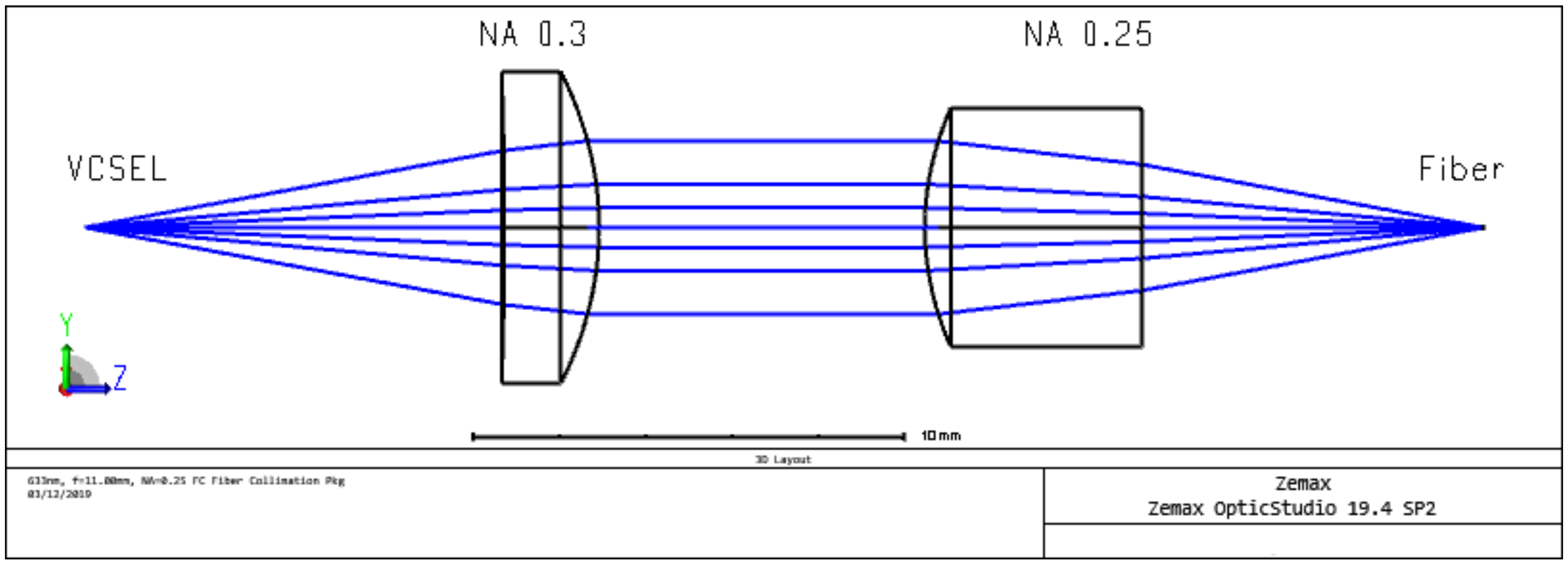
Optical coupling

- 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 125ºC. 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.

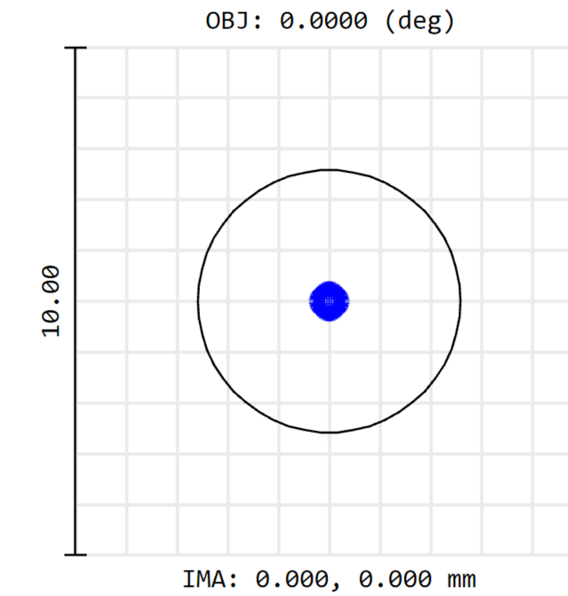
Optical coupling



Optical coupling



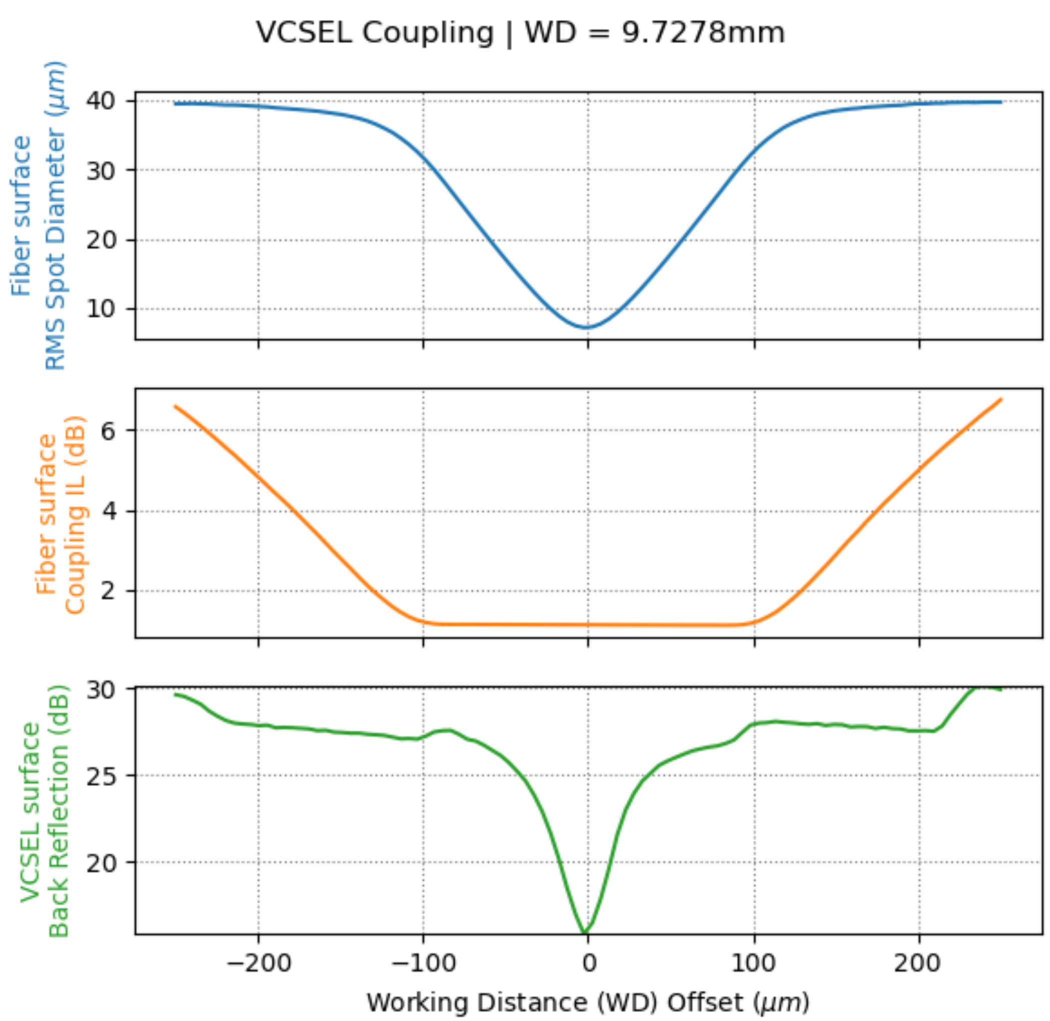
Ray tracing simulation



Light spot in the fiber end
(black circle represents the diffraction limit)

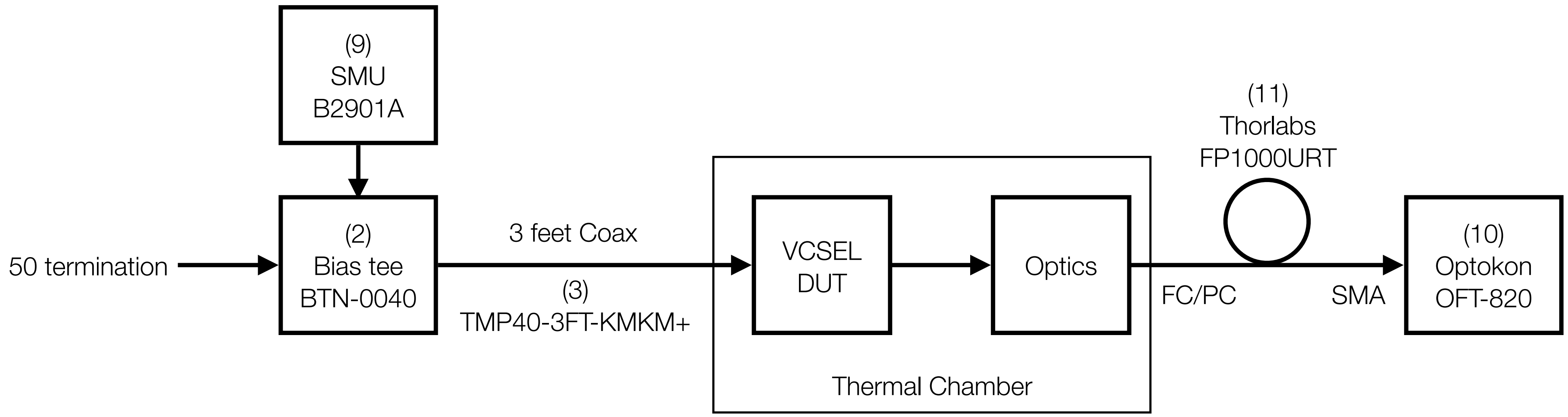
- Performance of the optical system has been simulated using ray tracing software
  - Simulation is done considering the VCSEL is a perfect point with NA=0.3 and wavelength 850 nm.
  - Spot size in the fiber is less than 1 um, which means the optical system is diffraction limited.
  - This is the best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

Optical coupling



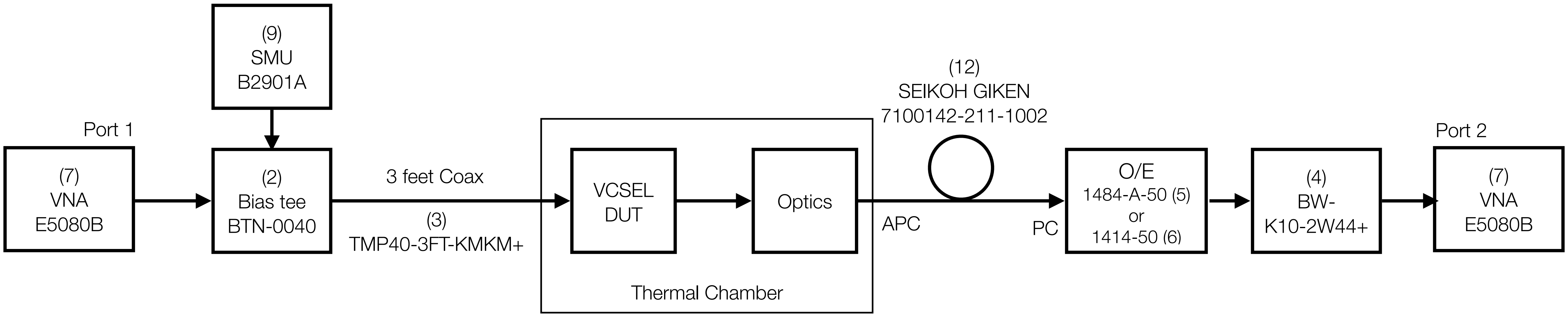
- The maximum reflection occurs when the spot size at the fiber end face is minimum.
  - This occurs at a working distance (WD) of 9.73 mm.
- If we generate a defocus by moving the WD, it is possible to reduce the Back-Reflections.
  - With a variation in the WD of 75um it would be possible to reduce 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

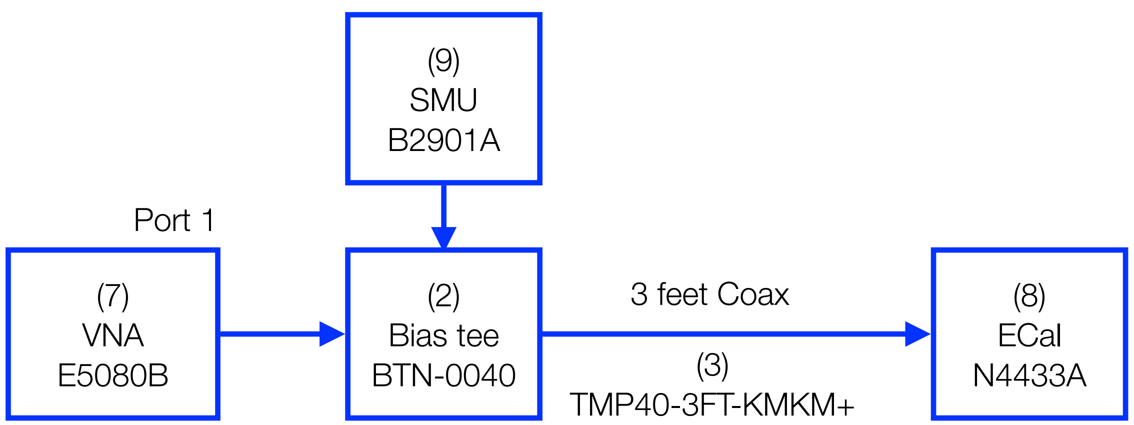
Test method — LIV



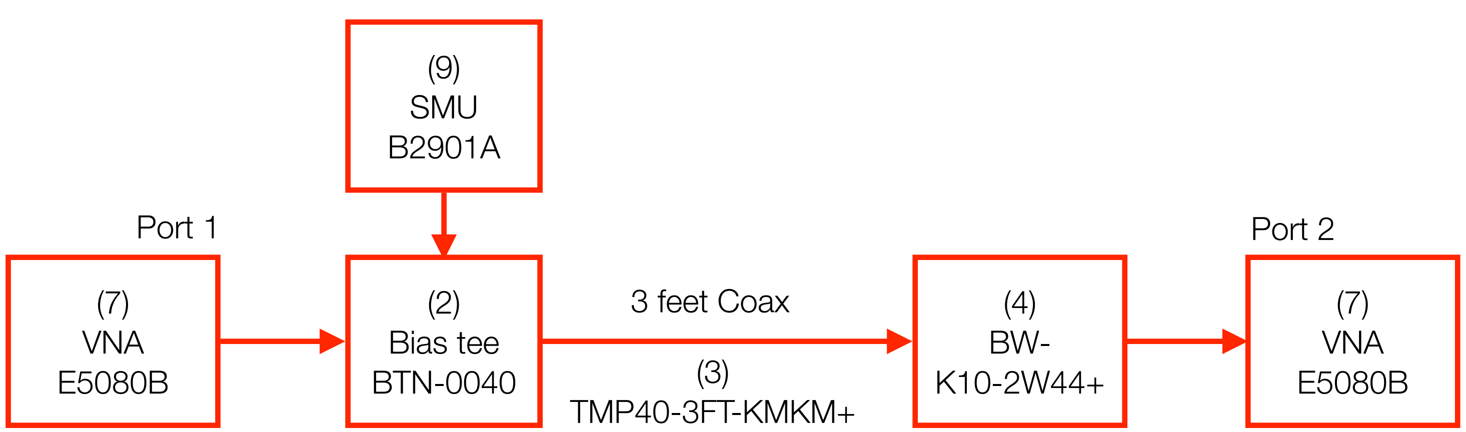
- Bias tee DC resistance is characterized: $R_{Bias\text{-}tee}$ = 6 Ohm (constant for the bias currents range)
- Optical power and forward voltage drop are measured in the following conditions:
  - I_{bias} = 0.02 to 2 mA in steps of 0.02 mA, and from 2.2 to 10 mA in steps of 0.2 mA.
  - T_{BS} = -40, 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

- $S21_{MEAS}$ (magnitude) and $Z11_{MEAS}$ (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_{bias} = 1 to 10 mA in steps of 0.5 mA
    - T_{BS} = -40, 0, 25, 85, 105, 125 ºC
- $Z11_{VCSEL+WB}$ is calculated from $Z11_{MEAS}$ and Sxy_{PCB}
    - Sxy_{PCB} are $S11_{PCB}$, $S22_{PCB}$, $S21_{PCB} = S12_{PCB}$, of the PCB + coax connector, obtained by OSL calibration, where VCSEL is replaced by open, short and reference impendance load
    - $Z11_{VCSEL+WB}$ is the Z11 of VCSEL including wire boding
    - 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 $Z11_{VCSEL+WB}$
- 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)
- $H_{VCSEL\text{-}INT}$ intrinsic VCSEL response is calculated from $S21_{MEAS}$, H_{OE}, H_{VI}, and f_P
- f_r (resonance frequency) and γ (damping rate) are MMSE fitted to $H_{VCSEL\text{-}INT}$

Test method — AC

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

$$S11_{MEAS} = \frac{Z11_{MEAS} - Zo}{Z11_{MEAS} + Zo}$$

$$S11_{VCSEL+WB} = \frac{S11_{MEAS} - S11_{PCB}}{S12_{PCB} \cdot S21_{PCB} + S22_{PCB} \cdot \left(S11_{MEAS} - S11_{PCB}\right)}$$

$$Z11_{VCSEL+WB} = Zo \cdot \frac{1 + S11_{VCSEL+WB}}{1 - S11_{VCSEL+WB}}; \quad \Re\left(Z11_{VCSEL+WB}\right) = R_S + \frac{R_J}{1 + \left(\frac{f}{f_p}\right)^2};$$

$$H_{VI} = \frac{S21_{PCB}\left(1 + S11_{VCSEL+WB}\right)}{1 - S22_{PCB} \cdot S11_{VCSEL+WB}} \cdot \frac{1}{Z11_{VCSEL+WB}}$$

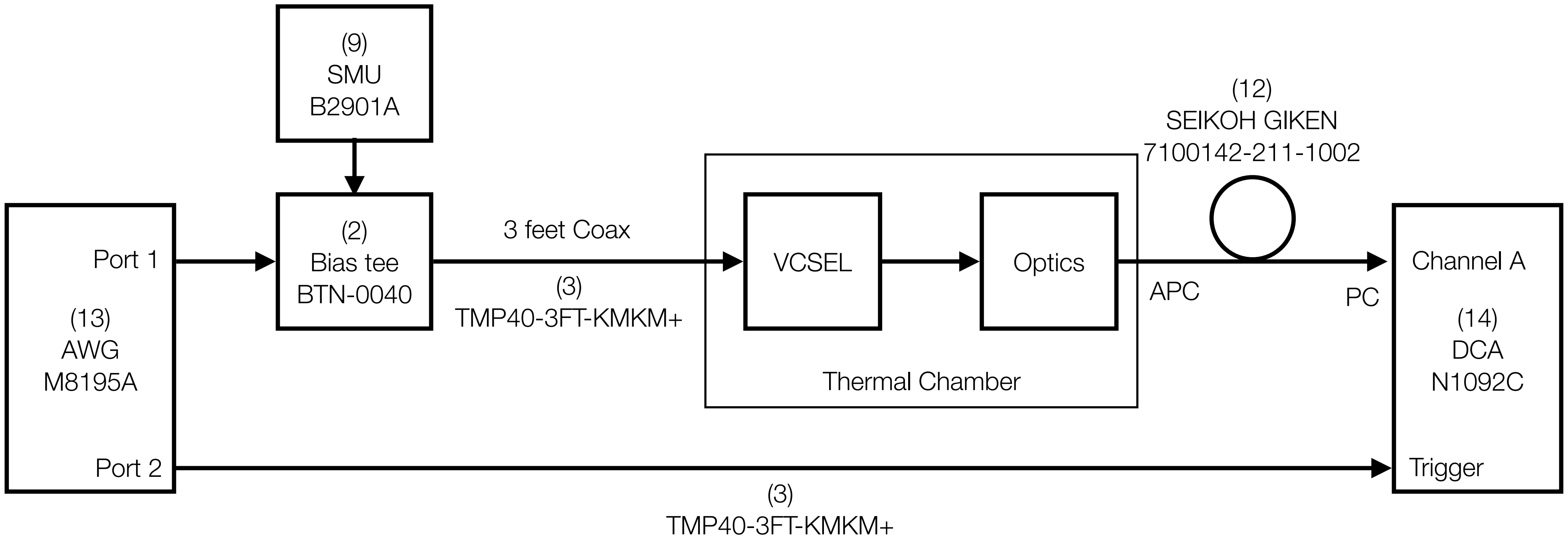
$$H_{VCSEL-EXT} = \frac{1}{1 + j\frac{f}{f_p}}; \qquad H_{VCSEL} = H_{VCSEL-EXT} \cdot H_{VCSEL-INT}$$

$$\left|H_{VCSEL-INT}\right| = \frac{\left|S21_{MEAS}\right|}{\left|H_{OE} \cdot H_{VI} \cdot H_{VCSEL-EXT}\right|}$$

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

- Small signal AC VCSEL response follows the model shown in several references, like [1], [2] and [3]

Test method — RIN

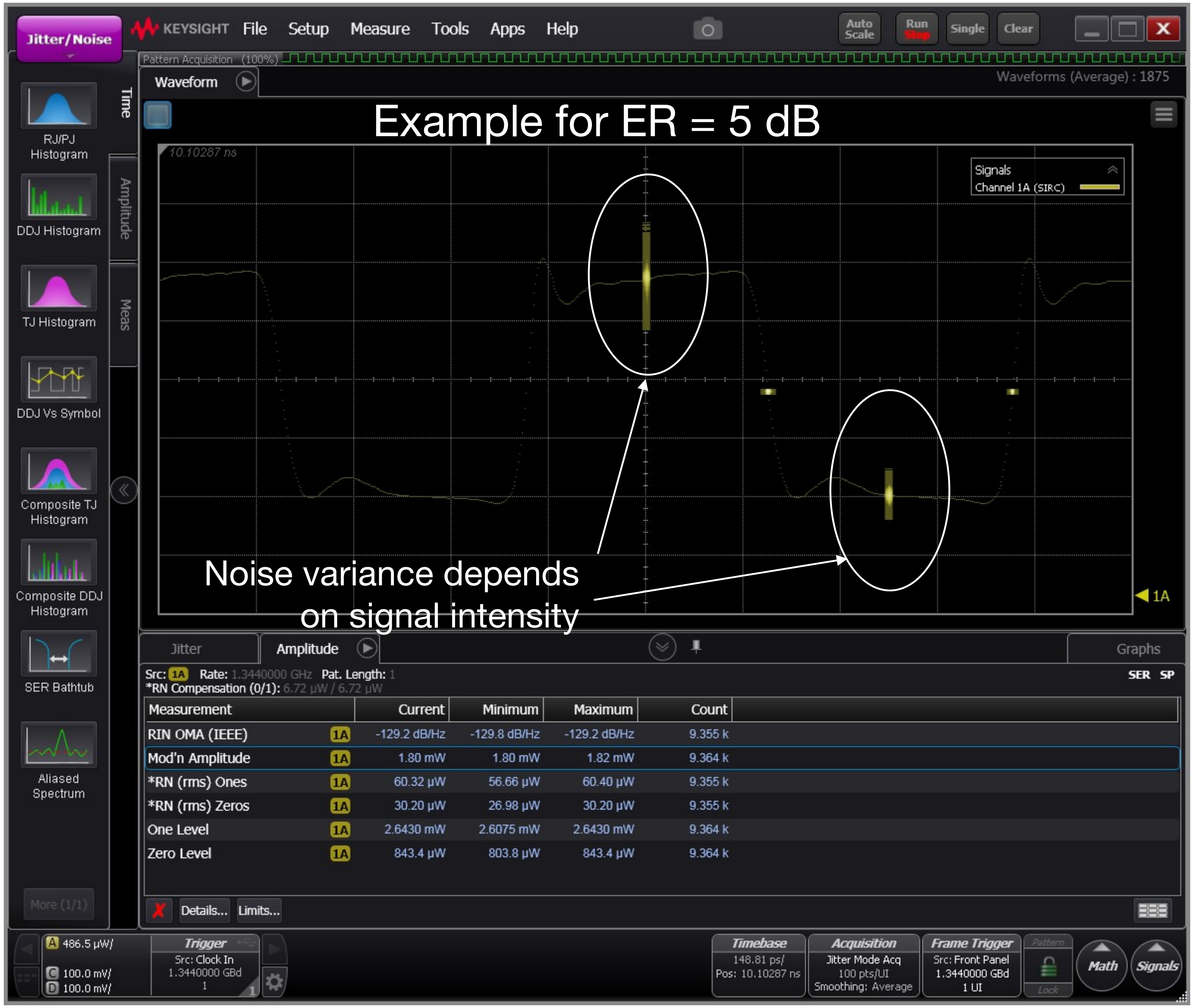


- Relative Intensity Noise (RIN) is measured in the following conditions:
    - I_{BIAS} - I_{TH}: from 1.5 to 6 mA in steps of 0.5 mA
    - ER: from 3 to 6 dB in steps of 1 dB
    - T_{BS}: -40, 0, 25, 85, 105, 125 °C
- Square signal pattern is used to separate the noise of ISI caused by VCSEL band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

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

- $RN_{one/zero}$: 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

References

- [1] Binhao Wang, Wayne V. Sorin, Samuel Palermo, Michael R. T. Tan, "Comprehensive vertical-cavity surface-emitting laser model for optical interconnect transceiver circuit design", Dec 2016, SPIE, Vol 55.
- [2] Guido Belfiore, Mahdi Khafaji, Ronny Henker, Frank Ellinger, "A Compact Electro-optical VCSEL Model for High-Speed IC Design", IEEE, 2016
- [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