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14. ABSTRACT
In the previous DURIP award (W911NF-13-1-0287), we reported the calibration data of the electrical loop back test of the SHF 12103A Dual Differential Channel 56 Gbps Bit Pattern Generator (BPG) and the eye diagram of the optical transmission produced with our (high speed integrated circuit group, HSIC) high speed microcavity VCSEL and the SHF 12103 BPG. In this case, only transmission BPG of devices can be characterized, however, the receiving data error transmission cannot be analyzed.
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Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

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Number of Papers published in peer-reviewed journals: 0.00

(b) Papers published in non-peer-reviewed journals (N/A for none)

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Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

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Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

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TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

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Graduate Students

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Names of Faculty Supported

NAME	PERCENT_SUPPORTED

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Total Number:

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Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

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Total Number:

Names of other research staff

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Inventions (DD882)

Scientific Progress

Technology Transfer

Bit Error Ratio Test Equipment for High Speed Vertical Cavity Transistor Laser & MicroCavity VCSEL and Photo Receiver

Final Report

September 1st 2014 – August 31st 2015

Contract: W911NF-14-1-0575

Submitted to:

U.S. Army Research Office

By:

Principle Investigator, Professor. Milton Feng

University of Illinois at Urbana Champaign

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Bit Error Ratio Test Equipment for High Speed Vertical Cavity Transistor Laser & MicroCavity VCSEL and Photo Receiver

(Final Report on Army Research Office under Grants W911NF-14-1-0575)

Abstract

In the previous DURIP award (W911NF-13-1-0287), we reported the calibration data of the electrical loop back test of the SHF 12103A Dual Differential Channel 56 Gbps Bit Pattern Generator (BPG) and the eye diagram of the optical transmission produced with our (high speed integrated circuit group, HSIC) high speed microcavity VCSEL and the SHF 12103 BPG. In this case, only transmission BPG of devices can be characterized, however, the receiving data error transmission cannot be analyzed.

In this DURIP award (W911NF-14-1-0575), we have recently purchased and received the SHF 11104A Dual Differential Channel 60 Gb/s Error Analyzer (EA) module, which is the counter part of the SHF 12103A BPG required for a complete data transmission analysis along with 70 GHz remote sampling. Both the electrical and optical calibration result of the EA and the data transmission performance of HSIC high speed microcavity laser (VCSEL) are presented.

Organization of Report

In this report, we outline the research progress we have achieved so far with the awarded grant. We received **$200,000** under the Army Research Office (ARO) contract W911NF-14-1-0575, $165,042 is used to purchase SHF 11104A Dual Differential Channel 60 Gb/s Error Analyzer and $34,958 is used to purchase for Agilent 86118A 70 GHz Remote Sampling Module. In total, the equipment budget spending is **$210,088** and **$10,088** from UIUC grant is used for supporting the remaining price difference and a purchase of New Focus 1484-A-50 22 GHz Photo Receiver. The main structure of the report is listed below.

I. Data modulation testing equipment purchased and setup
II. Test Equipment Specifications
III. Electrical qualifications at 50, 56 and 60 Gb/s on SHF 11104A EA
IV. Optical qualifications at 38, 39 and 40 Gb/s use of UIUC HSIC fabricated VCSEL and SHF 11104A Error Analyzer

I. Data Modulation Equipment Purchased and Setup

With the awarded contract grant, we have purchased the SHF 1104A, Agilent 86118A and New Focus 1484-A-50. The price breakdown is shown in Table I below.

Table I: Price breakdown of the data modulation testing equipment purchased by HSIC under the ARO contract W911NF-14-1-0575 and UIUC grant support

Equipment	Price
SHF 11104A Dual Differential Channel 60 Gbps Error Analyzer	$165,450.00
Agilent 86118A 70 GHz Dual Channel Remote Sampling Module	$37,988.00
New Focus 1484-A-50 22 GHz Photo Receiver	$6,650.00
Total	**$210,088.00**

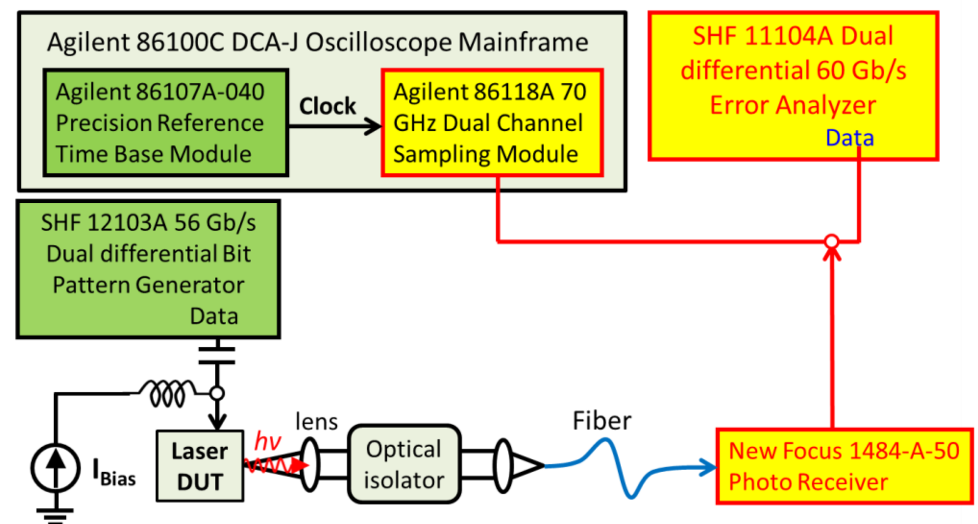


Figure 1A: Schematics of current HSIC optical measurement setup.

Figure 1A and 1B shows our updated optical measurement setup with the SHF bit error ratio test (BERT) system (SHF 12103A dual 56 Gb/s BPG and SHF 11104A dual 60 Gb/s EA), Agilent high speed oscilloscope (86107A-040 precision time base module and 86118A 70 dual GHz sampling module), and New Focus 1484-A-50 photo receiver for 850 nm wavelength detection. With this similar setup, replacing the 1484-A-50 with 1414-50 for 980 nm wavelength detection, we have demonstrated and reported error-free data transmission for an edge emitter transistor laser at 22 Gb/s[1].

[1] *R. Bambery, C. Wang, F. Tan, M. Feng, and N. Holonyak, Jr*., IEEE Photon. Technol. Lett., vol. 27, No. 6, pp. 600-603, March 15, 2015.

We plan to use the characterization on our fabricated energy efficient high speed data modulated laser devices such as, transistor laser and microcavity laser, obtained from the current setup to help us design next generation high speed laser devices that can achieve error-free data transmission up to and beyond 60 Gb/s. The dual channel capability of the BPG and EA system allows us to test bit error ratio at data rate to 120 Gb/s by integrating data multiplexer and de-mutiplexer modules in the near future .

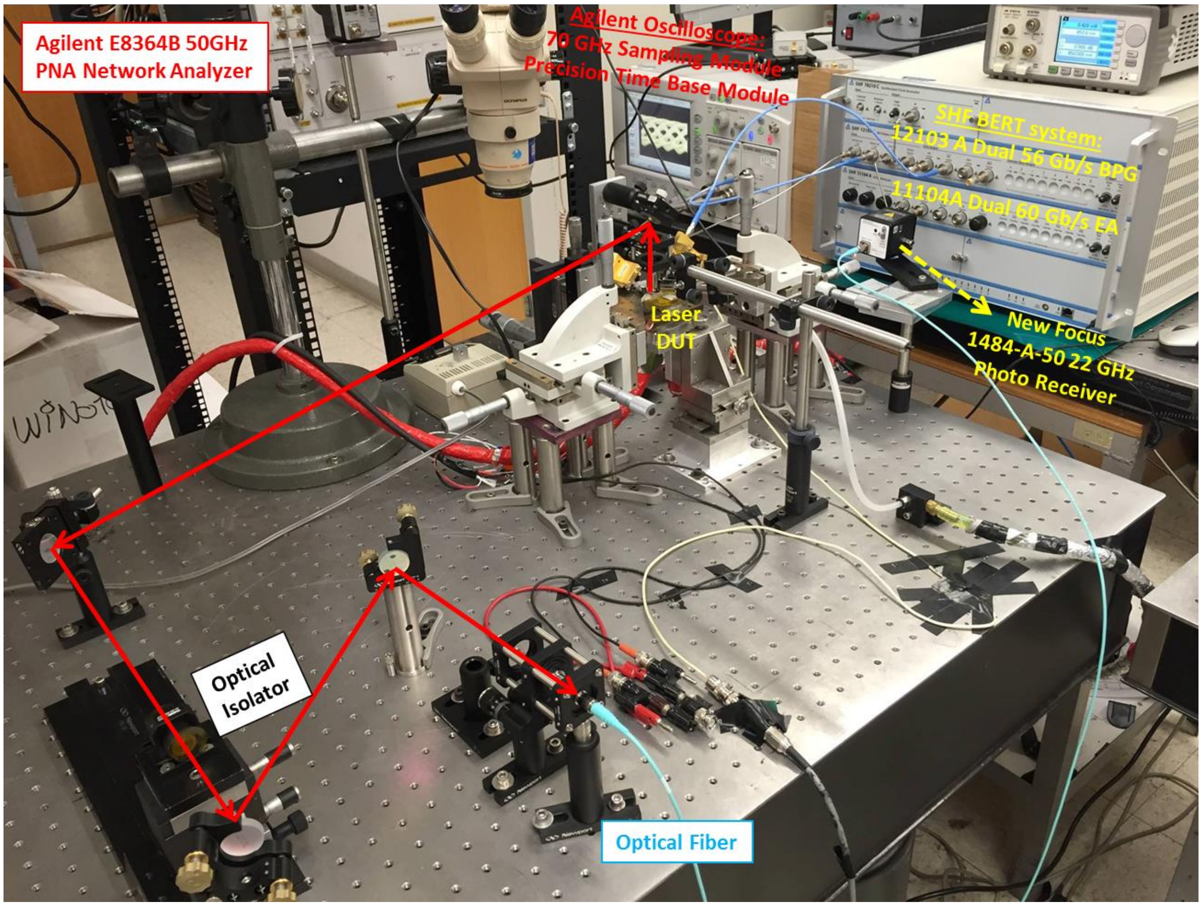


Figure 1B: Picture of current HSIC optical measurement setup.

II. Equipment Specifications

In this section, the specifications and functions of each purchased equipment listed in Table I will be discussed extensively.

II 1. SHF 11104A Dual Differential Channel 60 Gb/s Error Analyzer

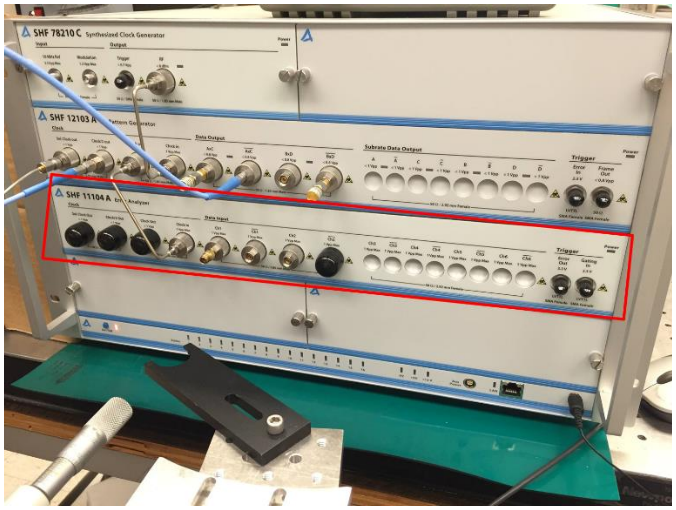


Figure 2: SHF 10001A mainframe with a SHF 12103A bit pattern generator (purchased earlier) and SHF 11104A error analyzer plug-in (red box, this work)

The SHF 11104A is a dual differential channel 60 Gb/s EA plug-in, which can be fitted into the SHF 10000 mainframes. It compares digital bit sequence such as standard pseudo-random bit sequences (PRBS) or users defined bit patterns from the BPG ($Data$ and $\overline{Data}$) to the data input and performs BERT at the receiving channels ($Channel$ and $\overline{Channel}$). The dual channel EA can perform BERT on two synchronized but independent data patterns up to 60 Gb/s per channel. Hence, combined with a DeMUX module in the future development, the EA can perform BERT on data transmission rate > 100 Gb/s. Figure 2 shows the SHF 10001A mainframe with a SHF 12103A BPG (purchased earlier) and SHF 11104A EA plug-in (red box). In Table II, the key specifications of the SHF 11104A dual differential channel 60 Gb/s EA are listed.

Table II: Key specs of SHF 11104A Dual Differential Channel 60 Gb/s Error Analyzer[2]

Parameter	Minimum	Typical	Maximum
Bit Rate (Gb/s)	8		60
Maximum AC Input Amplitude (mV_{pp})			900
Threshold Adjustment (mV)	-240	0	240
Delay / Clock Phase Adjustment (ps)	0		80
Sensitivity (mV)		25	50

[2] Data Sheet of SHF 11104A Dual Differential Channel 60 Gb/s Error Analyzer.

II 2. Agilent 86118A 70 GHz Dual Channel Remote Sampling Module

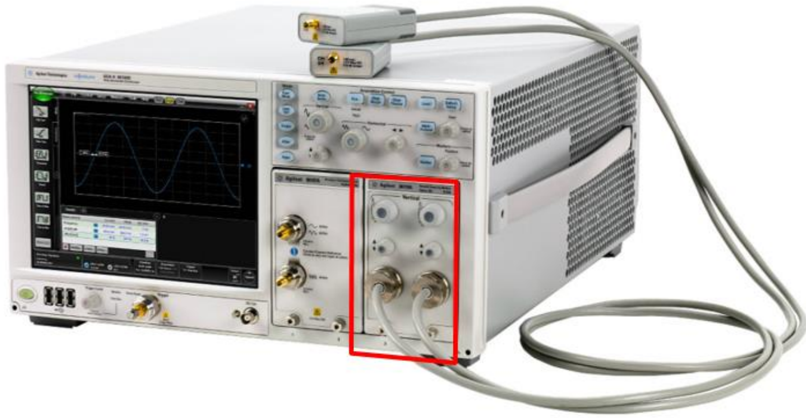


Figure 3: Agilent 86100C DCA-J main frame with 86107A-040 precision time base module (purchased earlier) and 86118A 70 GHz dual channel remote sampling module (red box).

The Agilent 86118A module provides an electrical bandwidth of 70 GHz on both sampling heads. Each sampling head is housed in a remote module by a light cable, which allows setup flexibility. With over 70 GHz of bandwidth, this module is intended for very high bit rate applications where signal fidelity is crucial. The specifications of this module is shown in Table III. Along with the 86107A-040 precision time base, we can now measure eye diagrams and perform waveform analysis with great precision at data rate above 50 Gb/s.

Table III: Key specs of Agilent 86118A 70 GHZ Dual Channel Remote Sampling Module[3]

Electrical channel bandwidth	50 and 70 GHz
Transition time (10% to 90%)	11.7 ps (30 GHz) 7 ps (50 GHz)
Characteristic RMS Noise	0.7 mV (50 GHz) 1.3 mV (70 GHz)
Maximum RMS Noise	1.8 mV (50 GHz) 2.5 mV (70 GHz)
DC accuracy (single marker)	±0.4% of full scale ±2 mV (50 and 70 GHz)
DC offset range	±500 mV
Input dynamic range	±400 mV
Maximum input signal	±2 V (+16 dBm)
Reflections (for 30 ps rise time)	20%

[3] Data Sheet of Agilent Infiniium DCA-86100C Wide-Bandwidth Oscilloscope –Mainframe & Module.

II 3. New Focus 1484-A-50 22 GHz Photo Receiver

Figure 4: New Focus 1484-A-50 22 GHz Photo Receiver.

The New Focus 1484-A-50 photo receiver is a GaAs detector based module, operating in the 800 to 865 nm wavelength range with multi-mode optical fiber input. It has a 3 dB bandwidth of 22 GHz; however, the frequency response roll-off is relatively slow and it has a 6 dB bandwidth at 38 GHz. On the other aspect, this photo receiver module is incorporated with a trans-impedance gain amplifier having a large inverse conversion gain, -110 V/W. This helps boost up the optical eye height at the receiving end of an optical data transmission link for a larger decision point opening without distorting the signal integrity. The key specifications of the New Focus 1484-A-50 photo receiver are listed in Table IV.

Table IV: Key specs of New Focus 1484-A-50 High-Speed Photo Receiver[4]

Wavelength Range	800-865 nm
Detector Material	GaAs
Conversion Gain	-110 V/W
Rise Time	16.5 ps
Optical Input	50-µm MM FC/PC
Bandwidth	22 GHz (-3 dB) 38 GHz (-6dB)
Output Impedance	50 Ω

[4] Data Sheet of New Focus 1484-A-50 High-Speed Photo Receiver

III. Electrical Qualification on SHF 11104A Error Analyzer (EA) at 50, 56 and 60 Gb/s

The SHF 11104A EA is capable of performing BERT at a dynamic and continuous range of bit rate from 8 Gb/s to 60 Gb/s. It provides a wide range of BERT decision point in threshold, -240 mV to 240 mV, and time delay, 0 ps to 80 ps, and an auto-search function to facilitate finding a decision point. Also, the EA can perform eye contour measurement on the receiving signal, which allows visually aided and time efficient decision point fine tuning. With the SHF 12103A BPG, we have performed electrical loopback qualification on the SHF 11104A EA. Having a qualified EA and BERT system (BPG+EA), we were able to proceed to optical measurements.

III 1. Electrical Loopback Qualification at 50, 56 and 60 Gb/s

We qualified the EA by following the standard experimental setup, inquired from SHF, and compare our measurement results to the provided specification. The schematic of the experimental setup is shown in Figure 5.

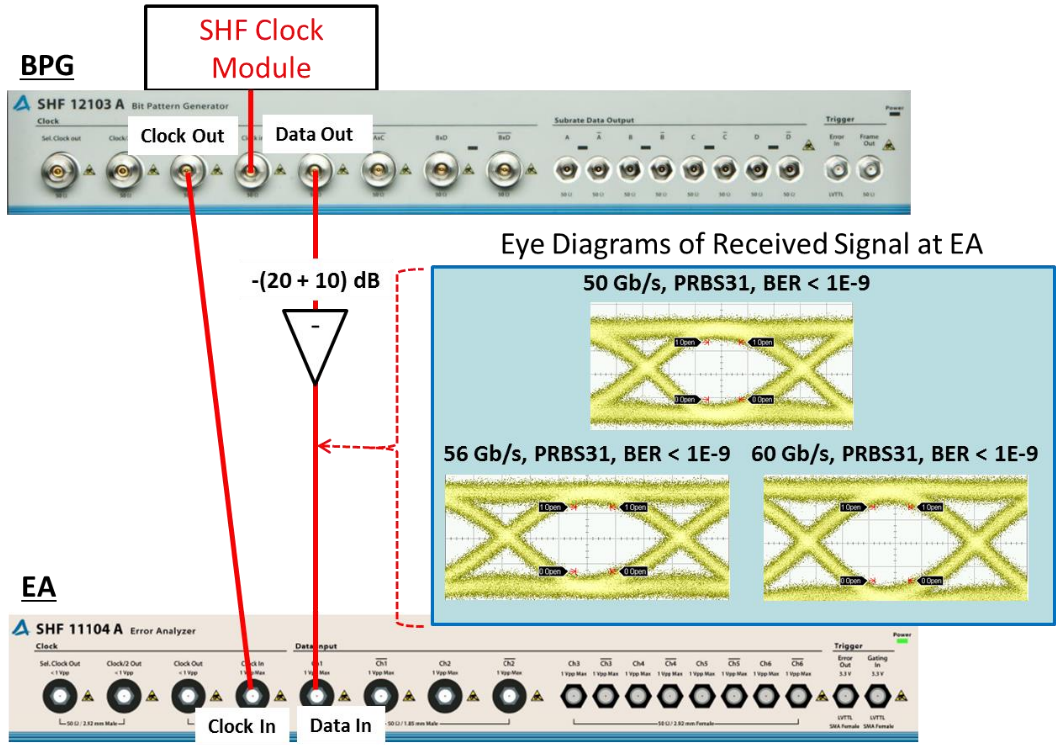


Figure 5: Schematics of the standard experimental setup to qualify the SHF 11104 EA by using the SHF 12103 A BPG. The BPG is externally clocked by the SHF clock module, and the clock output for the BPG is connected directly to the clock input of the EA through an electrical cable. The BPG data output is reduced down to 10~30 mV by a (20+10) dB attenuator combination and then connected directly to the data input of the EA through an electrical cable. The eye diagrams of the received signal shown are taken by our Agilent DCA 86100 oscilloscope with 86118A 70 GHz sampling heads and 86107A precision time base module.

To qualify the system with the setup shown in Figure 5, we first optimized the decision point for the reduced electrical signal by auto searching and fine-tuning manually and then performed BERT for 1 TB (1000 GB) with the EA. Next, we reduced the output V_{pp} on the BPG gradually until the BERT returns a BER of 1E-9 (or around 6.4 ~ 8.4E-10). The eye diagram of the signal resulted in a BER of 1E-9 at each data rate is recorded by our oscilloscope and the eye height of the signal is measured and compared with the specifications provided. Figure 6 shows the recorded eye diagrams with measurement and comparison.

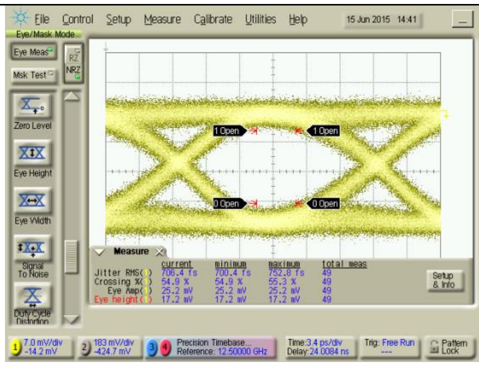
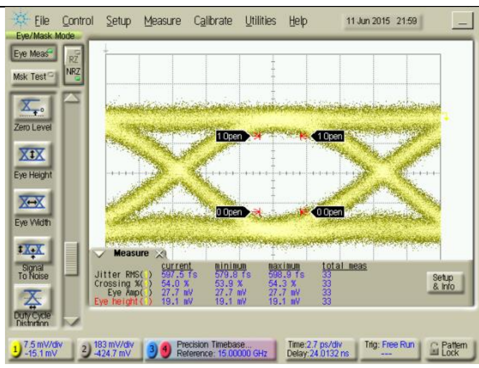
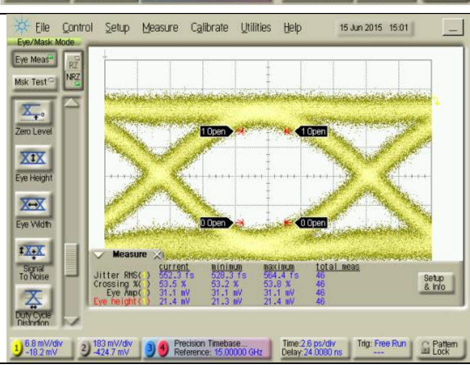
	Data Rate: **50 Gb/s** Pattern Type: **PRBS 31** Minimum eye height for BER < 1E-9: **17.2 mV / 18.2 mV (measured/ specs)**
	Data Rate: **56 Gb/s** Pattern Type: **PRBS 31** Minimum eye height for BER < 1 E-9: **19.1 mV / 21.6 mV**
	Data Rate: **60 Gb/s** Pattern Type: **PRBS 31** Minimum eye height for BER < 1 E-9: **21.4 mV / 21.9 mV**

Figure 6: Eye diagram of received reduced electrical signal and Comparison of HSIC measured minimum eye height for BER < 1E-9 to provided specifications[5].

[5] Inspection Report of SHF 11104A Dual Differential Channel 60 Gb/s Error Analyzer

IV. Optical BERT Testing on UIUC HSIC fabricated VCSEL at 38, 39 and 40 Gb/s

With the BERT system qualified, we could characterize the optical data transmission performance of our high speed microcavity laser (μCL). The initial testing was performed on our newly fabricated μCL (Process20150401) up to 40 Gb/s with an ambient temperature controlled at 25 ˚C. In Figure 6, the experimental setup of performing BERT is shown. The device under test was a HSIC 6.7 μm oxide confined optical aperture μCL and the device L-I and optical spectrum characteristics are shown in Figure 7. With the biasing point at I = 9 mA, the device under test exhibits a 3 dB optical bandwidth of ~ 20 GHz at 25 ˚C.

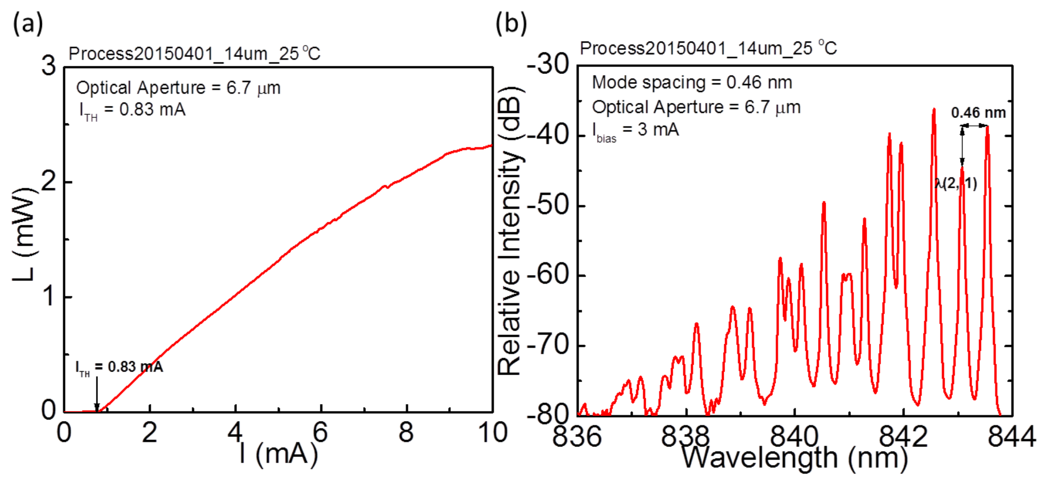


Figure 7: The (a) L-I and (b) Spectrum characteristics of the device under test. The laser threshold current, I_{TH}, of the μCL is 0.83 mA. The mode spacing between the fundamental mode, λ(1, 1), to the first second-order mode, λ(2, 1), is 0.46 nm which corresponds to an optical aperture opening of 6.7μm.

With the setup shown in Figure 8, we performed the optical BERT at transmission rate at 38, 39 and 40 Gb/s. The modulation peak-to-peak amplitude (V_{pp}) from the BPG was kept constant at 650 mV to maximize the optical eye height and the DC current bias (I_{bias}) was set to 9 mA to ensure a large enough optical light output through the optical isolator and an optical bandwidth ~ 20 GHz. The neutral density filter is used as a free space optical attenuator for characterizing BER versus optical power of the μCL. In order to prevent signal interference from back reflections, an optical isolator was incorporated in our experimental setup. The optical isolator used allows on average an 85% power transmission in the wavelength ranging from 830 nm to 870nm; at I_{bias} = 9 mA, we were able to couple 1.94 mW out of 2.25mW, which is more than 85%. The transmission bit pattern is a non-return-to-zero Pseudorandom Binary Sequence with a length of 2^7-1 bits, which is in short called PRBS7.

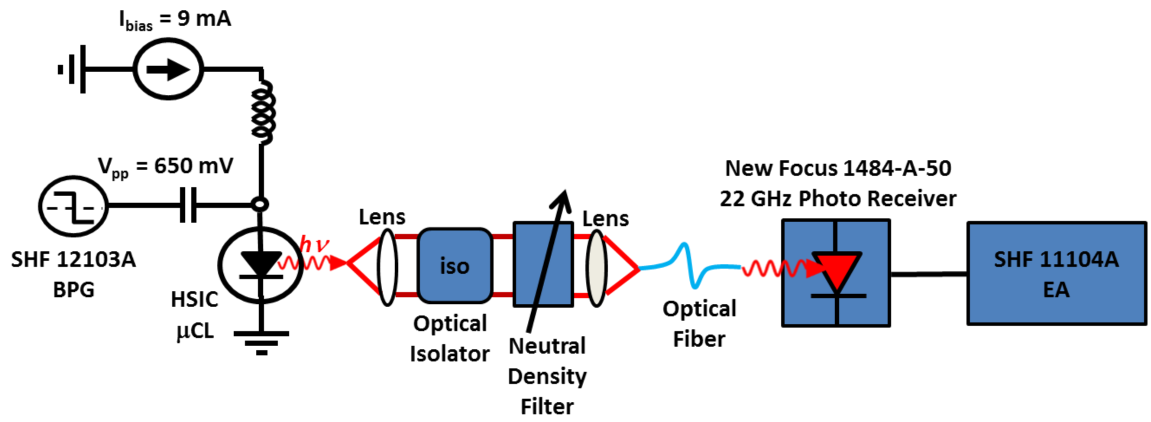


Figure 8: Experimental setup for performing optical BERT on our HSIC μCL with the SHF BERT system.

The eye diagrams, shown in Figure 9, at each transmission rate were taken by connecting the photo receiver to our Agilent DCA 86100 oscilloscope as a pre-indication of the data transmission performance. The eye diagrams at the transmission rates of 38, 39 and 40 Gb/s appear to have a clear opening for BERT decision point; nevertheless, an actual BERT needs to be performed to accurately and fully characterize the data transmission performance of the device under test. The result of the BERT is plotted as a semi-log plot with Log(BER) versus optical power and shown in Figure 10.

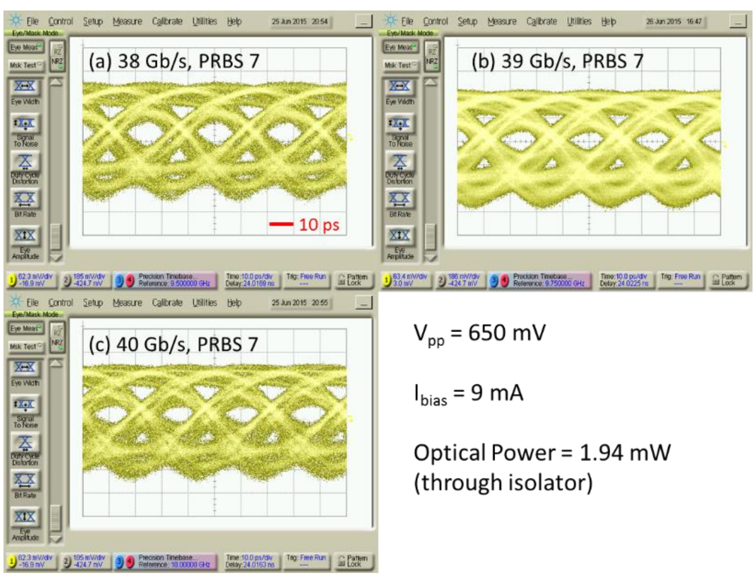


Figure 9: Optical output eye diagram of HSIC 7μm aperture μCL, modulated by PRBS 7 data pattern at transmission rate of: (a) 38 Gb/s, (b) 39 Gb/s and (c) 40 Gb/s. The device is biased at I = 9 mA, corresponds to a coupled optical power of 1.94 mw through optical isolator, and the amplitude of the modulation signal is at V_{pp} = 650 mV for each data modulation rate. The eye diagrams appear to be upside down because the New Focus 1484-A-50 photo receiver has an inverse trans-impedance

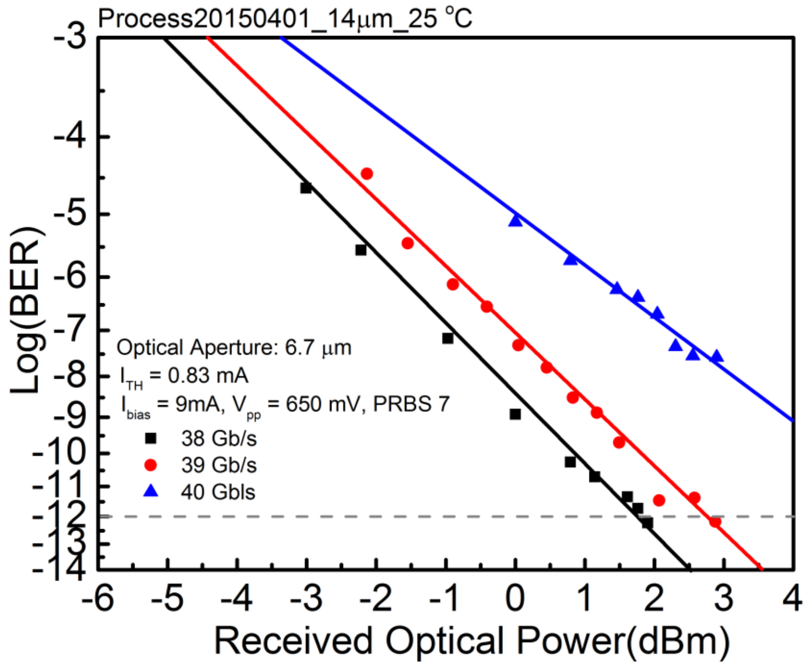


Figure 10: log(BER) versus optical power plot with results at 38, 39 and 40 Gb/s. The μCL under test was able to pass BERT, with log(BER) < -12, at 38 and 39 Gb/s, but was not able to pass at 40 Gb/s.

Each point on and below Log(BER) = -10 is recorded after a collection of 10 TB of transmission and each point above Log (BER) = -10 is recorded after a collection of 5 TB to avoid random errors and ensure BER stability. In standard optical BERT, the optical transmission link passes the test if it can achieve Log(BER) < -12 at a given optical power. As the results show, the optical link formed with the μCL under test was able to pass the BERT at 38 and 39 Gb/s, but was not able to pass at 40 Gb/s transmission rate yet. With increasing data rate, we see the fitted slopes of the measured points increase until they do not cross the -12 line at the maximum coupled power, 1.94 mW ≈ 3dB.

There are a few reasons why the optical link couldn't pass the BERT at 40 Gb/s. One of the reasons is that the maximum modulation V_{pp} from the BPG is limited at 650mV. The modulation V_{pp} can be boosted up by using external amplifiers and with higher modulation V_{pp}, it's likely that the optical link can pass 40 Gb/s and additionally 38 and 39 Gb/s at lower optical power given the same biasing point. We did not incorporate amplifiers in our experimental setup because the purpose of this experiment was to perform characterization using the SHF BERT system alone without external components.

Conclusion

With the purchased equipment from this award grant (W911NF-14-1-0575), we now have the full SHF BERT system to perform complete signal integrity analysis, such as eye diagram measurements and BERT, on our fabricated laser devices up to 60 Gb/s. In this report, we have shown **the calibration procedure and qualification** on the SHF BERT system at 50, 56 and 60 Gb/s. We also show the initial optical BERT results on our μCL. Typical HSIC microcavity VCSEL fabricated in our lab did pass BERT at 38 and 39 Gb/s. The SHF BERT system shows flexibility at data rate unlike our previous system and, in the near future, we intend to optimize the usage of the system in order to pass optical BERT at data rates from 8 to 60 Gb/s.