

รายการอ้างอิง

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ภาคผนวก

ภาคผนวก ก. บทความทางวิชาการที่ได้รับการเผยแพร่

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ประสิทธิภาพของตัวส่งสัญญาณทางแสงอัตรา 10 กิกะบิตต่อวินาที พร้อมระบบควบคุมอุณหภูมิ
ในการส่งแสงหลายความยาวคลื่นแบบหนาแน่น ด้วยระยะห่างช่องสัญญาณ 25 กิกะเฮิรตซ์
Performance of 10 Gb/s Optical Transmitter with Temperature Control System
in a 25-GHz Dense Wavelength Division Multiplexing Transmission

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บทคัดย่อ

บทความนี้นำเสนอการออกแบบตัวส่งสัญญาณทางแสงอัตราข้อมูล 10 Gb/s ด้วยเลเซอร์ที่มีมอดูเลเตอร์ชนิดดูดกลืนคลื่นไฟฟ้าอยู่ภายใน (Electro-Absorption Modulator Integrated Laser, EML) พร้อมระบบควบคุมอุณหภูมิที่ใช้ตัวควบคุมพีไอดี (Proportional Integral Derivative controller, PID controller) รวมทั้งผลการทดสอบของตัวส่งสัญญาณทางแสงในการรักษาเสถียรภาพของอุณหภูมิ เพื่อควบคุมให้ความคลาดเคลื่อนของความยาวคลื่นอยู่ในช่วง ± 10 pm ตามมาตรฐาน ITU-T G.692 (Frequency Deviation) และผลการทดสอบแผนภาพรูปตาของการส่งข้อมูลอัตรา 10 Gb/s ในการส่งแสงหลายความยาวคลื่นแบบหนาแน่น (Dense Wavelength Division Multiplexing, DWDM) จำนวน 3 ช่องสัญญาณด้วยระยะห่างช่องสัญญาณ 25 GHz ได้ตามมาตรฐาน SONET(OC-192)/SDH(STM-64) โดยไม่พิจารณาผลการลดทอน (Attenuation) และการกระจายโครมาติก (Chromatic Dispersion) ของสายต่อเส้นใยนำแสงสั้นๆ

คำสำคัญ : ตัวส่งสัญญาณทางแสง, ระบบควบคุมอุณหภูมิ, ตัวควบคุมพีไอดี, การส่งสัญญาณหลายความยาวคลื่นแบบหนาแน่น

Abstract

This article describes the design of 10 Gb/s optical transmitter using an Electro-Absorption Modulator Integrated Laser (EML) with temperature control system using a Proportional Integral Derivative (PID) controller. The experimental results show that the wavelength deviation of the optical transmitter is kept within ± 10 pm according to ITU-T G.692 (Frequency Deviation) standard. The measured 10 Gb/s eye-diagrams of 3 channels in 25-GHz DWDM transmission meet the SONET(OC-192)/SDH(STM-64) specification, without a considering attenuation and chromatic dispersion effects from short fiber patch cord.

Keyword: Optical Transmitter, Temperature Control System,

PID Controller, Dense Wavelength Division Multiplexing Transmission

1. บทนำ

ปัจจุบันระบบ DWDM ให้ความสำคัญในการเพิ่มความจุของการรับส่งข้อมูล โดยเพิ่มจำนวนช่องสัญญาณด้วยการลดระยะห่างระหว่างช่องสัญญาณให้แคบลง จาก 100 GHz เป็น 50 GHz, 25 GHz หรือแม้กระทั่ง 12.5 GHz ในช่วงความยาวคลื่น 1480 nm ถึง 1620 nm [1] ซึ่งระบบจะสามารถส่งข้อมูลตามระยะห่างช่องสัญญาณที่มีความแคบๆ อย่าง 25 GHz ซึ่งเท่ากับ 0.2 nm ที่ความยาวคลื่นประมาณ 1550 nm ได้นั้น เลเซอร์ภายในตัวส่งสัญญาณทางแสง จำเป็นต้องสร้างความยาวคลื่นที่ถูกต้องตลอดเวลา หรือมีความคลาดเคลื่อนน้อยกว่าหรือเท่ากับ 10 pm ตามมาตรฐาน ITU-T G.692 (Frequency Deviation) สำหรับการส่งข้อมูลแบบ DWDM อัตราข้อมูล 10 Gb/s ระยะห่างช่องสัญญาณ 25 GHz [2] ดังนั้นการนำ EML มาประยุกต์ใช้ในตัวส่งสัญญาณทางแสง โดยการปรับอุณหภูมิจนได้สเปกตรัมตามค่ามาตรฐาน ITU-T G.694.1 (DWDM frequency grid) [3] จึงเป็นทางเลือกที่เหมาะสมและคุ้มค่า [1]

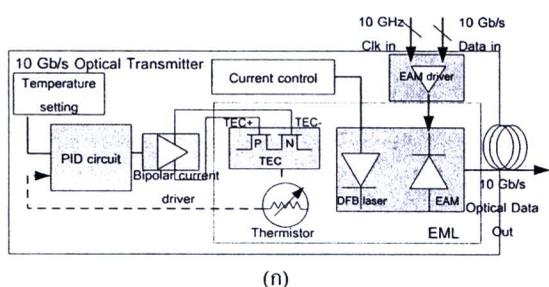
การปรับอุณหภูมิและการรักษาเสถียรภาพความยาวคลื่นของ EML โดยใช้ระบบควบคุมอุณหภูมิที่มีการทำงานร่วมกันของเทอร์มิสเตอร์ (Thermistor) และตัวระบายความร้อน (Thermo Electric Cooler, TEC) โดยระบบควบคุมดังกล่าวเป็นการควบคุมแบบป้อนกลับ (feedback control) ซึ่งมีหลายชนิด ในที่นี้เลือกใช้วงจรที่ง่ายต่อการศึกษาและนำมาประยุกต์ใช้งาน คือตัวควบคุมพีไอดี

บทความนี้จึงนำเสนอการออกแบบตัวส่งสัญญาณทางแสง 10 Gb/s พร้อมระบบควบคุมอุณหภูมิที่ใช้ตัวควบคุมพีไอดี ดังรายละเอียดในหัวข้อที่ 2 ซึ่งจะนำมาใช้งานในระบบ DWDM จำนวน 3 ช่องสัญญาณด้วยระยะห่างช่องสัญญาณ 25 GHz ดังรายละเอียดของแผนภาพการทดสอบในหัวข้อที่ 3 สำหรับผลการวัดเสถียรภาพความยาวคลื่น และแผนภาพรูปตาของการส่งข้อมูลแบบ DWDM 3 ช่องสัญญาณจะแสดงในหัวข้อที่ 4 ท้ายที่สุดคือการสรุปผลในหัวข้อที่ 5

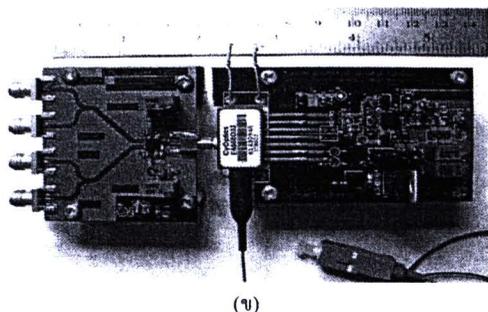
2. การออกแบบตัวส่งสัญญาณทางแสง

2.1. องค์ประกอบของตัวส่งสัญญาณทางแสง

องค์ประกอบหลักของตัวส่งสัญญาณทางแสง 10 Gb/s แสดงดังรูปที่ 1 (ก) มี 4 องค์ประกอบ คือ (1) EML เป็นเลเซอร์ชนิด Distributed Feed-Back (DFB) ที่มีมอดูเลเตอร์ชนิด Electro-Absorption Modulator (EAM) รวมอยู่ด้วย EML, E4560 ของบริษัท CyOptics ภายในโมดูลมี TEC และ เทอร์มิสเตอร์ สำหรับช่วยควบคุมอุณหภูมิของเลเซอร์, (2) EAM Driver ชิพ MAX 3941 ช่วยขยายสัญญาณ Common Mode Logic (CML) ให้ได้ระดับที่เหมาะสมกับ EAM, (3) ระบบควบคุมอุณหภูมิประกอบด้วยตัวควบคุมพีไอดีและตัวจ่ายกระแสสองขั้ว (Bi-polar current driver) ซึ่งคือชิพ MAX 8521 เชื่อมต่อกับเทอร์มิสเตอร์เพื่อวัดอุณหภูมิของเลเซอร์ ส่วน TEC มีหน้าที่ถ่ายเทความร้อนเข้า-ออกให้กับเลเซอร์, (4) วงจรควบคุมกระแสไบแอส เพื่อควบคุมกำลังแสงของเลเซอร์ ประกอบด้วย Voltage regulator (LM317) และตัวต้านทานปรับค่าได้



(ก)



(ข)

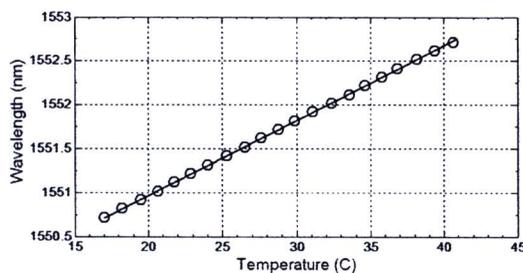
รูปที่ 1 (ก) แผนภาพองค์ประกอบของตัวส่งสัญญาณทางแสง 10 Gb/s

(ข) ตัวส่งสัญญาณทางแสงต้นแบบพร้อมระบบควบคุมอุณหภูมิ

การออกแบบแผ่นวงจรพิมพ์ของตัวส่งสัญญาณทางแสง 10 Gb/s นี้ จำเป็นต้องออกแบบลายเส้นสัญญาณแบบผลต่าง (Differential) ให้มีลักษณะเป็น Co-Planar เพื่อเพิ่มแบนด์วิดท์ของลายเส้นในการส่งสัญญาณระหว่างหัวต่อ SMA และชิพ MAX 3941 นอกจากนี้ต้องมีการควบคุมอิมพีแดนซ์ลักษณะให้คงที่เท่ากับ 100 โอห์ม โดยควบคุมความกว้างของเส้นสัญญาณซึ่งเป็นทองแดง และความหนาของชั้นไดอิเล็กทริกซึ่งเป็น FR4 ให้คงที่จากนั้นจึงบัดกรีประกอบตัวส่งสัญญาณทางแสงต้นแบบ แสดงดังรูปที่ 1 (ข)

2.2. ความสัมพันธ์ระหว่างอุณหภูมิกับความยาวคลื่นของเลเซอร์

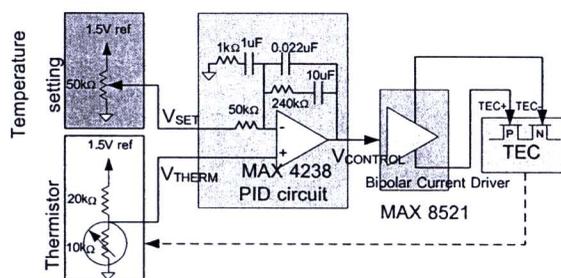
เลเซอร์ผลิตมาจากสารกึ่งตัวนำ จึงมีคุณสมบัติของพลังงานแบนด์แกป (Bandgap Energy) แปรผกผันกับอุณหภูมิตามความสัมพันธ์ของ Vashmi [4] ในขณะที่เดียวกันความยาวคลื่นแสงจะแปรผกผันกับ Bandgap Energy ดังนั้นการเปลี่ยนแปลงอุณหภูมิภายในจึงแปรผันโดยตรงต่อความยาวคลื่นที่เปล่งออกจากเลเซอร์ โดยได้ผลการทดลองวัดหาความสัมพันธ์ออกมาเป็นเชิงเส้นดังรูปที่ 2



รูปที่ 2 ความสัมพันธ์ระหว่างอุณหภูมิกับความยาวคลื่นของเลเซอร์

2.3. หลักการการควบคุมอุณหภูมิของเลเซอร์

การควบคุมอุณหภูมิของเลเซอร์ใช้หลักการควบคุมแบบป้อนกลับ แสดงดังรูปที่ 3 เริ่มจากการตั้งค่าอุณหภูมิที่ตัวต้านทานปรับค่าได้ 50 kΩ เป็นแรงดันตั้งค่า (V_{SET}) จากนั้นเปรียบเทียบกับแรงดันเทอร์มิสเตอร์ (V_{THERM}) ซึ่งบอกค่าอุณหภูมิของเลเซอร์ ได้เป็นผลต่างแรงดันที่จะถูกขยายด้วยชิพ MAX 4238 ซึ่งอยู่ภายในวงจรควบคุมพีไอดี เพื่อได้เป็นแรงดันควบคุม ($V_{CONTROL}$) ไปกำหนดขนาดและทิศทางของกระแส TEC ที่ออกจากตัวจ่ายกระแสสองขั้วชิพ MAX 8521 เพื่อควบคุมอุณหภูมิให้กับเลเซอร์ตามแผนภาพรูปที่ 3



รูปที่ 3 แผนภาพการควบคุมอุณหภูมิของเลเซอร์ [5]

2.4. การคำนวณค่าอุณหภูมิของเลเซอร์จากเทอร์มิสเตอร์

จากค่าแรงดัน V_{THERM} ที่ได้จากวงจรในรูปที่ 3 นำไปหาค่าความต้านทานเทอร์มิสเตอร์ (R_{THERM}) จากสมการที่ (1) และคำนวณค่าอุณหภูมิก่อนได้จากสมการที่ (2) โดยที่ β (ค่าคงที่เทอร์มิสเตอร์)

เท่ากับ 4140 และ R_0 (ค่าความต้านทานอ้างอิง) เท่ากับ 10440 Ω ที่อุณหภูมิห้อง ($T_0 = 298.15$ K) [6]

$$R_{THERM} = (20 \cdot 10^3 V_{THERM}) / (1.5 - V_{THERM}) \quad [\text{Ohm}] \quad (1)$$

$$R_{THERM} = R_0 \exp\left(\beta \left(\frac{1}{T} - \frac{1}{T_0}\right)\right) \quad [\text{Ohm}] \quad (2)$$

3. การทดสอบประสิทธิภาพของตัวส่ง

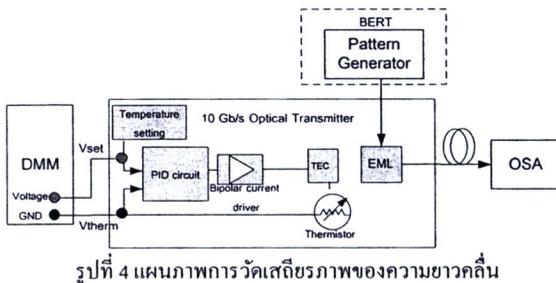
3.1 การวัดทดสอบเสถียรภาพของความยาวคลื่น

แผนภาพการวัดเสถียรภาพของความยาวคลื่นแสดงดังรูปที่ 4 โดยตัวส่งสัญญาณทางแสงทำงานต่อเนื่องและมีการมอดูเลตข้อมูล 10 Gb/s จาก Bit Error Rate Tester (BERT) ใช้ Optical Spectrum Analyzer (OSA) สังเกตการเปลี่ยนแปลงความยาวคลื่น ขั้นตอนการเก็บข้อมูลและการวัดสรุปได้เป็น 3 ขั้นตอน ดังนี้

ขั้นตอนที่ 1 หากความสัมพันธ์ระหว่าง V_{THERM} กับความยาวคลื่นของเลเซอร์ โดยปรับ V_{SET} จากนั้นบันทึกค่า V_{THERM} ในช่วงการทำงานของเลเซอร์ ± 0.2 nm ความละเอียด 0.1 nm จากค่าความยาวคลื่นกลาง 1551.72 nm จะได้ความสัมพันธ์ดังกล่าว

ขั้นตอนที่ 2 บันทึกผลต่างแรงดันระหว่าง V_{SET} และ V_{THERM} จาก Digital Multi-Meter (DMM) เก็บข้อมูลทุก 2 นาทีเป็นเวลา 24 ชั่วโมง

ขั้นตอนที่ 3 คำนวณความคลาดเคลื่อนของความยาวคลื่น โดยนำผลต่างแรงดันจากขั้นตอนที่ 2 คูณกับความชันของความสัมพันธ์ที่ได้จากขั้นตอนที่ 1 จะได้ค่าความยาวคลื่น ณ เวลาต่างๆ

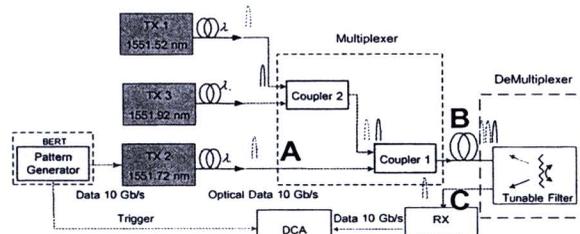


รูปที่ 4 แผนภาพการวัดเสถียรภาพของความยาวคลื่น

3.2 การวัดแผนภาพรูปตาของการส่งข้อมูลแบบ DWDM

แผนภาพการทดสอบแสดงดังรูปที่ 5 ประกอบด้วย 2 ส่วน คือ **ภาคส่งสัญญาณ** ตัวส่งสัญญาณทางแสงทั้งสามมีความยาวคลื่นแสงที่ 1551.52 nm (Tx1), 1551.72 nm (Tx2) และ 1551.92 nm (Tx3) ในการส่งข้อมูลแบบ DWDM 3 ช่องสัญญาณระยะห่าง 25 GHz ตามมาตรฐาน ITU-T G.694.1 แต่มีการมอดูเลตข้อมูล 9.9532 Gb/s (OC-192/STM-64) จาก BERT เฉพาะ Tx2 เท่านั้น จากนั้นทั้งสามช่องสัญญาณจะถูกมัลติเพล็กซ์รวมกัน ด้วยตัวคู่ต่อสัญญาณทางแสง (Optical Coupler) 2 ตัว เข้ายังสายต่อเส้นใยนำแสงสั้นๆ

ภาครับสัญญาณ ทางภาครับจะแยกเฉพาะแสง 1551.72 nm ด้วยตัวกรองแสงแบบปรับได้ (Tunable filter) JDSU MAP 200 โมดูล mTBF-A1 โมเดล G ซึ่งมีค่า -3dB แบนด์วิดท์ 0.25 nm [7] จากนั้นตัวตรวจจับแสงชนิดถล่มทลาย (Avalanche Photo-Detector, APD) จะแปลงแสงเป็นสัญญาณไฟฟ้าและได้แผนภาพรูปตา 10 Gb/s แสดงผลด้วยเครื่อง Digital Communication Analyzer (DCA) โมดูล 86150B ซึ่งต้องมีสัญญาณ Trigger ส่งตรงมาจาก BERT

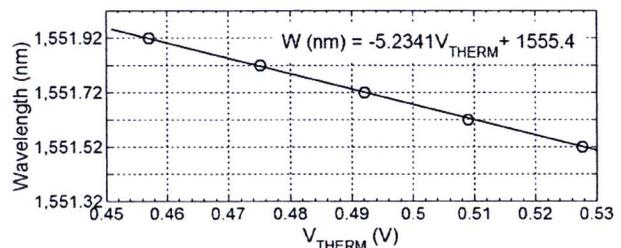


รูปที่ 5 แผนภาพการส่งข้อมูลแบบ DWDM 3 λ ระยะห่าง 25 GHz

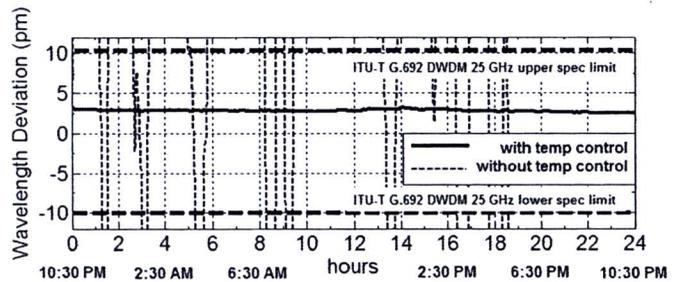
4. ผลการวัดทดสอบ

4.1 ผลการวัดทดสอบเสถียรภาพของความยาวคลื่น

การวัดเสถียรภาพของความยาวคลื่นของตัวส่งสัญญาณทางแสงเปรียบเทียบกับ 2 กรณี คือ กรณีที่มีและกรณีที่ไม่มีระบบควบคุมอุณหภูมิ โดยให้เลเซอร์ทำงานที่ความยาวคลื่น 1551.72 nm ได้ผลความสัมพันธ์ระหว่าง V_{THERM} กับ ความยาวคลื่นของ EML ดังรูปที่ 6 ซึ่งมีสัดส่วนการเปลี่ยนแปลงความยาวคลื่นต่อแรงดันเป็น -5.2341 nm/V และมีผลการทดสอบเสถียรภาพของความยาวคลื่นใน 24 ชั่วโมงแสดงดังรูปที่ 7



รูปที่ 6 ความสัมพันธ์ระหว่าง V_{THERM} กับความยาวคลื่น



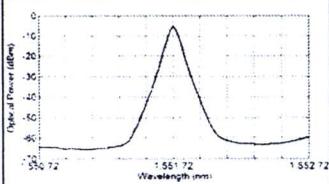
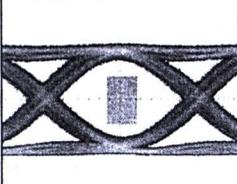
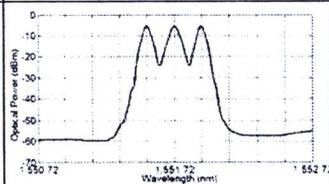
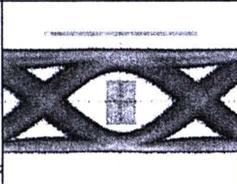
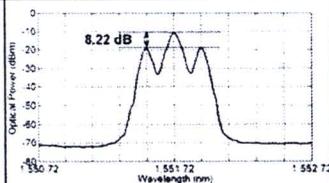
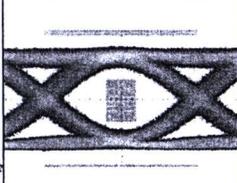
รูปที่ 7 เสถียรภาพความยาวคลื่นขณะที่มีและไม่มีระบบควบคุมอุณหภูมิ

จากผลการวัดเสถียรภาพปรากฏว่าระบบที่ไม่มีการควบคุมอุณหภูมิ มีความยาวคลื่นคลาดเคลื่อนมากกว่า ± 10 pm จากความยาวคลื่นที่กำหนด 1551.72 nm ในขณะที่มีระบบควบคุมอุณหภูมิจะให้ค่าความยาวคลื่นคลาดเคลื่อนได้ $\approx +3$ pm คิดว่ามาตรฐาน ITU-T-G.692 [2] ซึ่งมีค่า ± 10 pm ดังนั้นจึงสามารถนำตัวส่งสัญญาณทางแสงพร้อมระบบควบคุมอุณหภูมินี้ ไปใช้ในการส่งข้อมูลแบบ DWDM ได้

4.2 ผลการวัดแผนภาพรูปตาในการส่งข้อมูลแบบ DWDM

การวัดสเปกตรัมของแสงและแผนภาพรูปตาจากการวัดในแต่ละจุด ซึ่งได้แก่ จุด A, B และ C แสดงดังรูปที่ 5 ซึ่งมีผลการวัดดังตารางที่ 1 โดยมีค่าชดเชยกำลังแสงทั้ง 3 ช่องสัญญาณตั้งไว้ที่ -5 dBm

ตารางที่ 1 สเปกตรัมและแผนภาพรูปตาแต่ละจุดในรูปที่ 5

จุด	สเปกตรัมของแสง (10 dBm/div, 0.2 nm/div)	แผนภาพรูปตา (40mV/div, 17ps/div)
A		
B		
C		

จุด A แสดงการส่งสัญญาณแสง 10 Gb/s แบบช่องเดี่ยวมีแผนภาพรูปตาเปิดกว้าง แต่เมื่อมีผลคrosstalkของสัญญาณข้างเคียงเข้ามาซึ่งแสดงสเปกตรัม ณ จุด B สังเกตว่าแผนภาพรูปตามีความหนาแน่นขึ้นจนทำให้แผนภาพรูปตาแคบลงอย่างเห็นได้ชัด ซึ่งเป็นผลจากการรบกวนระหว่างช่องสัญญาณ (Interchannel Crosstalk) และหลังจากภาครับได้แยกช่องสัญญาณ 1551.72 nm ออกด้วย Tunable Filter แสดงสเปกตรัม ณ จุด C Filter สามารถลดกำลังแสงของช่องสัญญาณข้างเคียงได้ 8.22 dB ที่ระยะห่าง 25 GHz ทำให้แผนภาพรูปตาคลับมาเปิดกว้างขึ้น แต่ยังคงมีผลของ Interchannel Crosstalk เหลืออยู่เมื่อเทียบกับ จุด A

จากผลการวัดแผนภาพรูปตาทั้ง 3 จุดพร้อม Eye mask มาตรฐาน OC-192/STM-64 ซึ่งแสดงเป็นกรอบสี่เหลี่ยมผืนผ้าบริเวณกึ่งกลางของแผนภาพรูปตาสรุปได้ว่า ตัวส่งสัญญาณทางแสงสามารถส่งข้อมูลได้ตามมาตรฐานดังกล่าว ในการส่งข้อมูลแบบ DWDM 3 ช่องสัญญาณด้วยระยะห่าง 25 GHz โดยไม่พิจารณาปัญหา Attenuation และ Chromatic dispersion อันเนื่องจากสายต่อเส้นใยนำแสงสั้นๆ ซึ่งทั้งสองปัญหาไม่มีผลต่อเสถียรภาพของความยาวคลื่นแต่อย่างใด

5. สรุป

บทความนี้ได้อธิบายการออกแบบตัวส่งสัญญาณทางแสงอัตรา 10 Gb/s พร้อมระบบควบคุมอุณหภูมิ ผลการทดสอบประสิทธิภาพของวงจรควบคุม โดยแสดงเป็นค่าเสถียรภาพของความยาวคลื่นได้ ± 3 pm ซึ่งดีกว่า ± 10 pm และผลการวัดแผนภาพรูปตาของตัวส่งสัญญาณทางแสง ผ่านมาตรฐาน SONET (OC-192)/SDH (STM-64) บนระบบ DWDM 3 ช่องสัญญาณด้วยระยะห่าง 25 GHz

6. กิตติกรรมประกาศ

บทความนี้ได้รับทุนสนับสนุนงานวิจัยจาก สถาบันวิจัยและพัฒนาอุตสาหกรรมโทรคมนาคม (TRIDI) สำนักงานคณะกรรมการกิจการโทรคมนาคมแห่งชาติ (กทช) และได้รับการสนับสนุนเครื่องมือวัดทดสอบจากโครงการเสริมสร้างความเชื่อมโยงระหว่างภาควิชาวิศวกรรมไฟฟ้าและภาคเอกชนทางด้านการวิจัยและพัฒนา และโครงการกลุ่มเชี่ยวชาญแห่งจุฬาลงกรณ์มหาวิทยาลัย ด้านการสื่อสารคลื่นแสงและความเร็วสูง

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Design and Performance of 10 Gb/s Optical Receiver in 50-GHz DWDM Transmission over 40-km SSMF

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ABSTRACT

This paper describes the design of 10 Gb/s optical receiver, which consists of an Avalanche Photo-Detector (APD) and a Clock & Data Recovery (CDR) circuit. All components are successfully integrated onto the 4-layered FR-4 PCB, using two types of signal paths: differential microstrip and single-ended CB-CPW. Their dimensions are optimally chosen for matching impedance, according to the ADS simulations. The receiver's performance has been evaluated under 3 impairments: jitter, interchannel crosstalk and fiber dispersion. The Periodic Jitter (PJ) is added to analyze histograms and measure the receiver's jitter tolerance. The crosstalk and dispersion effects on eye-diagram are demonstrated via the testbed of 50-GHz Dense Wavelength Division Multiplexing (DWDM) transmission over 40-km Standard Single Mode Fiber (SSMF). The measured jitter tolerance proves that this receiver can pass the SONET (Synchronous Optical Network) mask standard with Bit Error Rate (BER) below 10^{-12} . The recovered eye-diagrams show that this design can reduce both crosstalk and dispersion effects. The power penalty of this receiver is determined from the BER plot to be within 2-dB standard limit.

Keywords: Optical Receiver, Jitter, Crosstalk, Dispersion

1. INTRODUCTION

Optical fiber communication has become popular due to its tremendous bandwidth and low attenuation. The main focus of research and development is to increase data rate of all components inside both optical transmitter and optical receiver up to multi Gb/s range. The current bit rate per channel is 40 Gb/s for chipset [1] and optical modulator [2]. Meanwhile, the performance criteria of high-speed data transmission are constantly better. For example, a typical 10^{-9} BER is replaced by 10^{-12} BER or error-free transmission. Moreover, the jitter impairment deteriorates as data rate increases. The jitter generation of optical transmitter as well as the jitter tolerance of optical receiver must be exceptional; otherwise, the BER will be worse. In order to sustain such strict criteria, some additional circuits are required, such as, an equalizer and CDR circuit with integrated low-noise amplifier.

The total transmission capacity of WDM system is upgradable either by increasing a number of channels or decreasing a channel space between adjacent channels. To lower a system's cost, the Coarse WDM (CWDM) is generally chosen with fixed 20 nm channel spacing. In

contrast, the DWDM system has many channel spacings: 200, 100, 50, 25 and 12.5 GHz (equivalent to 1.6, 0.8, 0.4, 0.2 and 0.1 nm at ~ 1550 nm wavelength) according to the ITU-T G.694.1 standard of spectral grids for WDM application. This tight spacing requires expensive lasers with more stable and narrower spectral widths. Multiple optical transmitters and receivers can be integrated into one WDM transceiver, for instance, 4 channel \times 10 Gb/s transceiver for CWDM [3] and DWDM [4] at 200 GHz spacing. Most DWDM systems use 100 GHz spacing [5]. The 50 and 25 GHz [6] spacings are preferred for higher capacity, however, with additional power penalty due to a severe channel crosstalk.

DWDM system is usually installed as core networks with a standard transmission distance of 2, 15, 40, 80, 120 or 160 km. This distance is another performance criterion. Two impairments occur when using a long SSMF: fiber attenuation and Group Velocity Dispersion (GVD). First, the attenuation can be compensated by optical amplifiers, such as Erbium Doped Fiber Amplifier (EDFA). Second, the GVD, which causes pulse spreading, can be mended by using Dispersion Compensation Fiber (DCF) that has a large negative dispersion. For the 10 Gb/s system over 40 km long SMF at 1550-nm wavelength, both EDFA and DCF are deployed according to the ITU-T G.691 standard [7]; however, they raise the total cost of system.

In this work, the design of 10 Gb/s optical receiver is described. It consists of an APD, a CDR circuit and a 155 MHz reference clock soldered on a 4-layered Printed Circuit Board (PCB). The aim of this paper is to demonstrate a successful integration of those commercially available components onto a commonly manufactured FR-4 PCB, not a specially required high-performance dielectric. Using the licensed Advanced Design System (ADS) software and other free ware, the routes and dimensions of signal paths between every pair of components were simulated for matching impedance and optimally chosen under some realistic constraints, such as the limitations of PCB fabrication, the smallest PCB, a minimal number of design cycles, and the lowest cost per prototype. Different PCB designs were simulated, but only the best two versions were selected for fabrication. This optical receiver was assembled as our first prototype and it can pass all the following tests.

The receiver's performance has been evaluated under three impairments: jitter, interchannel crosstalk and GVD. To analyze jitter, the PJ is injected into PG to measure jitter histograms and the jitter tolerance of receiver. The resulted jitter tolerance shows that this receiver can pass

the SONET mask standard with BER below 10^{-12} across the jitter frequency range between 0.7 and 80 MHz. Subsequently, to analyze crosstalk and GVD, three 50-GHz DWDM channels are transmitted over 40 km long SSMF and the received 10 Gb/s eye-diagrams are measured. This transmission condition is properly chosen from those described standards and in agreement with a specification of 10 Gb/s optical transmitters used in the experimental testbed. Since the receiver can reduce both crosstalk and dispersion effects via its CDR circuit, the recovered eye-diagrams can successfully pass the STM-64/OC-192 data mask standard. The BER performance of this receiver is also measured showing the power penalty at 10^{-9} BER within 2-dB standard limit.

The remainder of this paper is organized as follows. Section 2 explains about jitter, interchannel crosstalk and GVD. Section 3 describes the design and components of 10 Gb/s optical receiver. Section 4 shows block diagrams of three measurement setups: jitter histogram, jitter tolerance, and DWDM transmission testbed. Section 5 analyzes the results, including jitter histograms, jitter tolerance, eye-diagrams and BER plot. Finally, section 6 gives a conclusion.

2. EVALUATED IMPAIRMENTS

There are three impairments that will be evaluated here. They are jitter, interchannel crosstalk, and GVD. Their basic knowledge is explained in section 2.1 to 2.3, respectively.

2.1 Jitter

Jitter is a time variation of data's bit period. It will cause the frequency variation of recovered clock signal at a receiver. Consequently, the period of data sampling will fluctuate, possibly causing some errors in the recovered data. If the jitter becomes too severe, the clock signal may be unrecoverable by a CDR circuit and the receiver will eventually stop functioning.

The total jitter can be classified into two components [8]: Deterministic Jitter (DJ) and Random Jitter (RJ), as shown in Fig. 1.

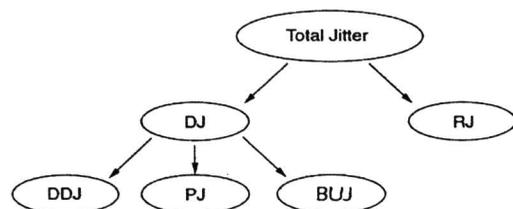


Fig.1: Classification of Jitter

RJ having a Gaussian histogram is always included in transmitted data. It is inherently present due to the thermal noise in electronic components as well as the shot noise from a random characteristic of arriving photons at a photodetector. Within DJ, the jitter can be further grouped as: Data Dependant Jitter (DDJ), Periodic Jitter (PJ), and Bounded Uncorrelated Jitter (BUJ). DDJ arises from the combination of Duty Cycle Distortion (DCD)

and Inter-Symbol Interference (ISI). BUJ is caused by signal crosstalk. And, PJ is caused by modulation and periodic noise, such as a power supply's noise. In this paper, only PJ is investigated due to its deterministic characteristic, in addition to the inherent RJ. Since PJ can be explicitly experimented by injecting a sinusoidal wave into PG, it is commonly applied as in the cast of jitter tolerance test. In contrast, DDJ strongly depends on a chosen data pattern whereas BUJ depends on an amount of crosstalk. In this experimental setup, DDJ and BUJ are fixed due to the selected 10 Gb/s Non Return to Zero (NRZ) Pseudo Random Bit Sequence (PRBS) $2^{31}-1$ data pattern and a constant amount of crosstalk. Hence, both DDJ and BUJ are excluded from this investigation.

Jitter can be described by the equation (1) [9], which is equivalent to phase modulation.

$$S(t) = P(2\pi f_d t + \varphi(t)) \quad (1)$$

where $\varphi(t)$ is jitter added into the signal $P(t)$ with f_d frequency, and $S(t)$ is the final signal with added jitter. For example, Fig.2 shows a clock signal with added PJ. In this case, PJ is a sinusoidal wave. The period of 'Ideal Clock' is varied by PJ's amplitude, resulting in the 'Jittered Clock' signal.

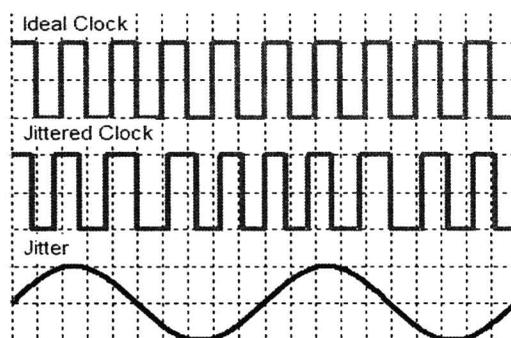


Fig.2: Example of Clock Signal with Periodic Jitter

The jitter analysis requires many histograms of data's bit crossing in the eye-diagram measurement mode. As previously mention, the Gaussian histogram is a result of total RJ in a system, as shown in Fig. 3 (a). If PJ is added, the final histogram will become a double Gaussian shape due to the multiplication of a Gaussian histogram with a double peak histogram of PJ, as shown in Fig. 3 (b).

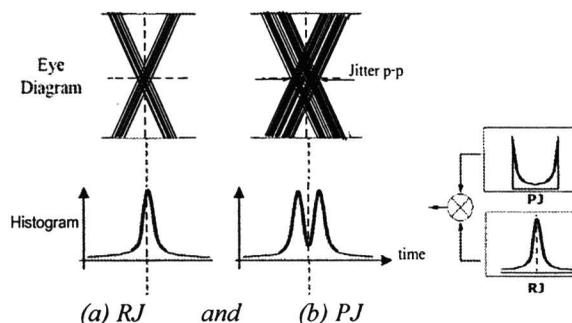


Fig.3: Bit Crossing of Eye-diagram and Jitter Histogram

The amount of jitter is indicated either by peak-to-peak (p-p) or root-mean-square (rms) value. p-p is the maximum jitter read at a bit crossing of eye-diagram as shown in Fig. 3, whereas rms is the average of squared jitters. The unit of jitter is in second or UI (Unit of Interval), which is the ratio of jitter in second over a bit period. The UI is preferred since it clearly indicates how severe the jitter impairment occurs within one bit period.

As described earlier, jitter will cause some errors in recovered data due to the variation in sampling period of recovered clock. The optical receiver will stop recovering data once the added jitter gets too high. This maximum amount of tolerable jitter, so called the jitter tolerance, must be measured across a frequency range. In this experiment, the PJ with a fixed frequency is injected into a system. Its amplitude is gradually increased until the system's BER reduces to a typical value of 10^{-12} . This maximum amplitude of PJ is then recorded in the jitter tolerance plot, as shown in Fig. 4 [8]. Same procedures are repeated at other frequencies. The result is compared to a standard threshold line. If it lies above a threshold, the optical receiver passes standard. Otherwise, it fails any record falls below a threshold.

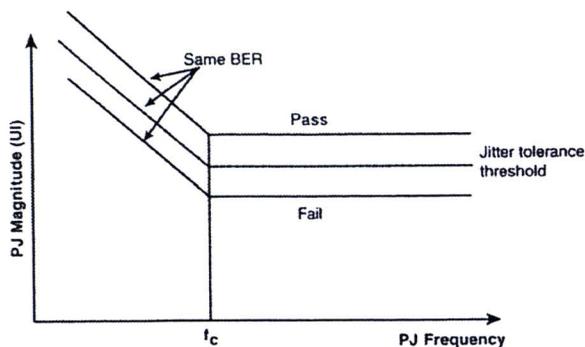


Fig.4: Standard Plot of Jitter Tolerance

2.2 Interchannel Crosstalk

The interchannel crosstalk is those unwanted power from neighbouring WDM channels that leaks into the desired channel. Thus, the interfering signals will have different wavelengths. This differs from the intrachannel crosstalk, which is more severe with interfering signals having the same wavelength as desired signal. To remove interchannel crosstalk, the optical de-multiplexer with a narrow bandpass profile and sharp wavelength cut-off is required. Any crosstalk will cause an increase in BER and power penalty. The amount of interchannel crosstalk will vary depending on the selected channel spacing. This crosstalk can be determined from the bandpass profile of optical de-multiplexer via an Optical Spectrum Analyzer (OSA). Furthermore, the crosstalk will become additional noise; resulting in the thicker lines at both data bit '1' and '0' on eye-diagram as proven later in the experimental result section. These thicker lines are clearly observed by examining the vertical histograms of bit '1' and '0' levels as well as the eye height, as shown in Fig. 5. Since the variances of both bits' histograms will slightly increase,

the measured eye height of recovered eye-diagram will also slightly decrease.

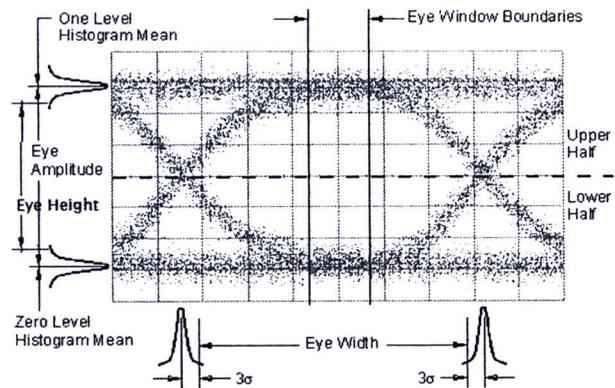


Fig.5: Eye-diagram with Histograms

2.3 Group Velocity Dispersion (GVD)

GVD is also known as the chromatic dispersion or the intramodal dispersion. It will cause pulse spreading along SMF due to the different wavelengths propagate at different speeds. GVD is a combination of material and waveguide dispersions. The variation of refractive index depending on transmitted wavelength will give rise to material dispersion; whereas the different designs of SMF's refractive index profile will control waveguide dispersion, which is always a negative value. GVD is also in effect in Multi Mode Fiber (MMF); however, the intermodal dispersion is more dominant over GVD.

Since the GVD causes pulse spreading into adjacent data bits, which is so-called Inter Symbol Interference (ISI). This increases the rise time and fall time of data's eye-diagram as well as reduces the BER performance. The rise/fall time due to GVD, t_{GVD} , can be calculated from the equation (2) [10], where $D(\lambda)$ is the total GVD of SMF at a transmitted wavelength λ , L is the total length of SMF, and σ_λ is the 3-dB spectral width of transmitted optical signal.

$$t_{GVD} \approx |D(\lambda)| L \sigma_\lambda \quad (2)$$

For SSMF, the value of $D(\lambda)$ can be calculated from the equation (3) [10], where λ_0 is the wavelength with zero dispersion, and S_0 is the dispersion slope of total GVD at wavelength λ_0 .

$$D(\lambda) = \frac{\lambda S_0}{4} \left[1 - \left(\frac{\lambda_0}{\lambda} \right)^4 \right] \quad (3)$$

Otherwise, the value of $D(\lambda)$ between 1500 and 1620 nm wavelength can be determined from the measurement line shown in Fig. 6. $D(\lambda)$ calculated from the equation (3) is also plotted in Fig. 6 as a dash line. The solid measurement line was exported from Agilent 860384B Photonic Dispersion and Loss Analyzer after testing the 40-km SSMF used in this experiment. According to the

40-km SSMF's datasheet from its manufacturer, λ_0 is specified at 1313.5 nm and S_D is 0.086 ps/(nm².km).

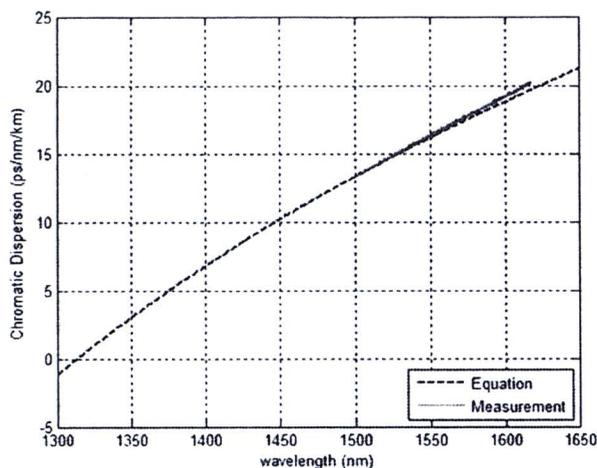


Fig.6: Group Velocity Dispersion versus Wavelength

After calculating the rise/fall time due to GVD, t_{GVD} , from equation (2), the total rise/fall time of system, t_{sys} , can be calculated from the equation (4) [10], where t_{tx} is the rise/fall time due to an optical transmitter and t_{rx} is the rise/fall time due to an optical receiver. The total rise/fall time of system must be less than 70 percent of bit period for that transmission system to work.

$$t_{sys} = \sqrt{(t_{tx}^2 + t_{rx}^2) + t_{GVD}^2} \quad (4)$$

3. DESIGN OF 10 Gb/s OPTICAL RECEIVER

In optical fiber communication, the optical receiver typically uses two types of semi-conductor based photodetector: Positive-Intrinsic-Negative (PIN) and Avalanche Photo-Detector (APD). PIN has lower noises and requires a lower biased voltage than APD. However, APD has a better power sensitivity and a larger output, and thus is more suitable for long distance applications. For these reasons, the APD is chosen in this design.

The 10 Gb/s optical receiver prototype consists of three main components as shown in Fig. 7: (1) APD with Trans-Impedance Amplifier (TIA) (R197AL module from Cyoptics), (2) Clock and Data Recovery (CDR) with Limiting Amplifier (LA) (MAX3991 chip from Maxim), and (3) 155.52 MHz reference clock (CCPD-033 module from Crystek). The datasheets and schematic block diagrams of R197AL module and MAX3991 chip are available in reference [11] and [12], respectively.

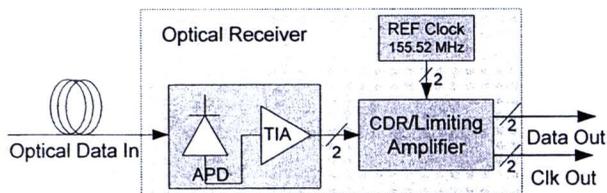


Fig.7: Components of 10 Gb/s Optical Receiver

All components were soldered on the 4-layered PCB as shown in Fig. 8. After 10 Gb/s NRZ optical data is launched into the optical receiver prototype via a fiber pigtail on the left of picture, APD converts this optical signal into photocurrent, and then TIA converts it into small voltage signal. Next, LA amplifies this signal up to a constant digital output and sends it through CDR. The differential 10 GHz clock output is recovered by Phase Lock Loop (PLL), whereas the differential 10 Gb/s data output is regenerated by D-Flip-Flop (DFF) inside CDR. Both data and clock outputs are CML (Common Mode Logic) levels and have SMA connectors, located on the right and the bottom of picture. The chosen CDR requires a reference clock input at either 1/64 (=155.52 MHz) or 1/16 (=622 MHz) of transmitted data rate, which is exactly at 9.9532 Gb/s (STM-64).

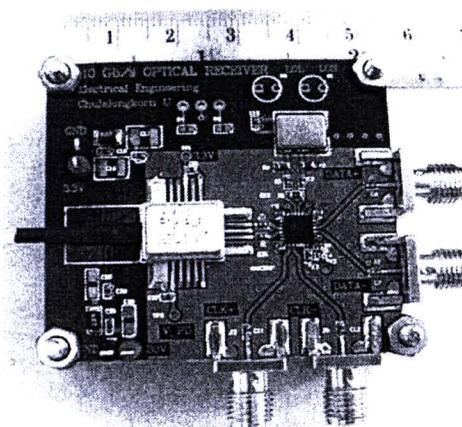


Fig.8: 10 Gb/s Optical Receiver Prototype

The cross-sectional view of 4-layered PCB on FR-4 dielectric is shown in Fig. 9. The signal planes are on top and bottom layers, whereas the ground and power planes are on the 2nd and 3rd layers, respectively. All dimensions are properly chosen from the cost and limitations of PCB fabrication as well as the impedance simulation results.

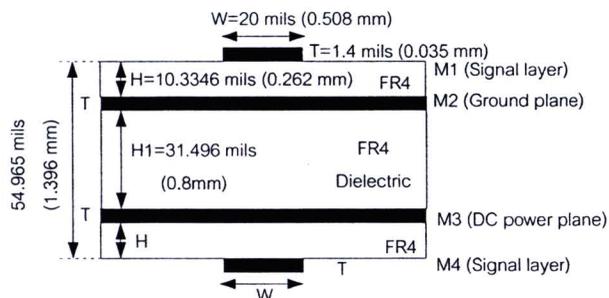


Fig.9: Cross-sectional View of 4-layered PCB

Since both data and clock outputs are differential signals, the differential microstrip line must be applied. Its cross-sectional view is shown in Fig. 10 (a). In some sections of signal paths, the single-ended Conductor-Backed Co-Planar Waveguide (CB-CPW) is chosen over a typical single-ended microstrip line due to its better control of the characteristic impedance, according to the

simulation results given in Fig. 11. The cross-sectional view of CB-CPW is shown in Fig. 10 (b).

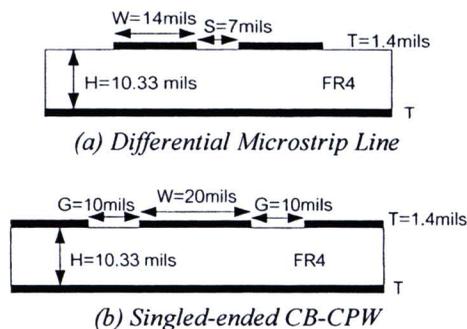


Fig.10: Cross-sectional Views of Signal Paths

Several dimensions and routing of signal paths were simulated using the licensed ADS software and a free ware PolarSi8000. Their results are compared with the computation of equations in reference [13]. For example, Fig. 11 compares the impedance results of G-parameter in singled-ended CB-CPW. Two versions of PCB design (straight versus curved lines) with the shortest path and the best matching impedance were fabricated.

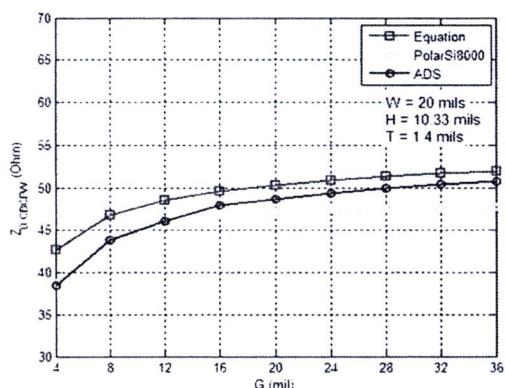


Fig.11: Simulation Results of CB-CPW

The measurement results of S_{21} parameters between singled-ended microstrip and CB-CPW are compared in Fig. 12. The 3-dB bandwidth of microstrip is 8.2 GHz, whereas the CB-CPW's bandwidth is beyond 10 GHz.

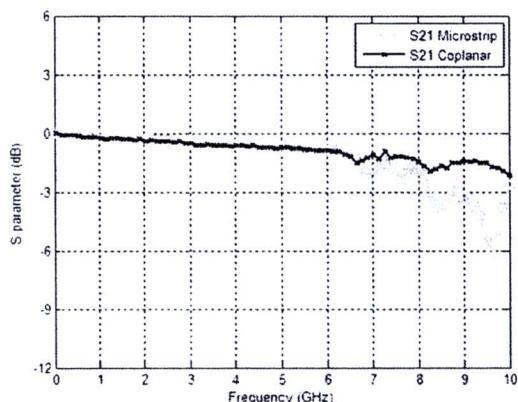


Fig.12: Measurement Results of S_{21} Parameter

To prove the matching impedance of designed PCB, the differential Time Domain Reflectometer (TDR) 54754A module from Agilent Technologies is connected to both data+ and data- outputs without a CDR chip, their differential impedance is measured to be 97.67 ohms, which is almost equal to the required 100 ohms, as shown by the marker in Fig. 13.

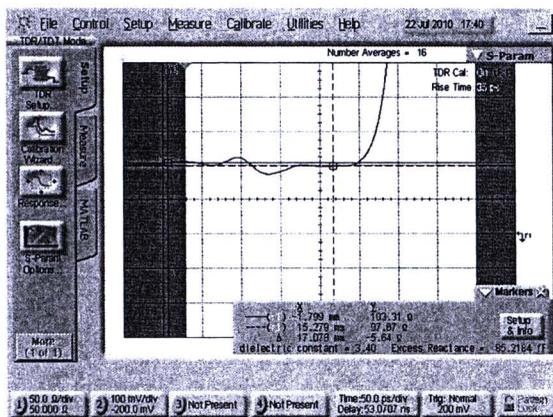


Fig.13: TDR Measurement of Differential Data Lines

Table 1 compares the main parameters of prototype with two commercial transceivers (from Finisar and Bookham), considering only parameters from receiver side. The prototype's bit rate can be varied by changing the reference clock's frequency, whereas the commercial transceivers do not have a fixed bit rate as they receive the reference clock from their host boards. The output level and rise/fall time are within the same ranges. This prototype can detect a wide range of wavelength and has a better sensitivity of -25.3 dBm at 10^{-12} BER. Thus, it provides a larger dynamic range of (-2-(-25.3)) 23.3 dB. In addition, the maximum penalty of prototype read from BER plot is 0.8 dB (in section 5.3), which is less than that of the other two transceivers.

Table 1: Comparison of Receiver's Parameters

Electrical Characteristics	Receiver Prototype	Finisar [14]	Bookham [15]	Unit
Data Bit Rate	9.95328	9.95-10.7	9.95-10.75	Gb/s
Different Output	575-725	340-850	360-770	mV
Data Output Rise/Fall Time	30	38	24	ps
Power Consumption	0.71 (Rx)	3.5 (Tx&Rx)	3.5 Tx&Rx)	W
Optical Characteristics				
Center Wavelength	1280-1610	1270-1600	1530-1560	nm
Receiver Sensitivity @ 10^{-12}	-25.3	-24	-15.8	dBm
Receiver Overload	-2	-7	-1	dBm
Maximum Path Penalty @ 40km (20 ps/nm/km)	0.8	2 (@ 80 km)	2	dB

4. MEASUREMENT SETUPS

There are two main sets of measurement setups: jitter measurements and DWDM transmission testbed, as given in section 4.1 and 4.2, respectively.

4.1 Jitter Measurements

Jitter measurements have two setups: jitter histogram and jitter tolerance, as given in section 4.1.1 and 4.1.2, respectively. 10 Gb/s NRZ PRBS $2^{31}-1$ data is generated by the BER Tester (BERT) Agilent N4901B-100 that has Pattern Generator (PG) and Error Detector (ED). The transmitter (TX) using an Electro-absorption Modulation Laser (EML) [16] sends optical data through a Variable Optical Attenuator (VOA) to simulate fiber loss. The receiver (RX) recovers 10 Gb/s data for either (1) the eye-diagram measurement by DCA (Digital Communication Analyzer) Agilent 86150B 15 GHz optical / 20 GHz electrical module [17] as shown in Fig. 14, or (2) the BER measurement by ED as shown in Fig. 15. The sine wave from Signal Generator (SG) is fed to the delay input port of BERT to generate added PJ.

4.1.1 Jitter Histogram from Eye-diagram

To measure jitter histogram as in Fig. 14, the DCA must be set properly to measure the histogram of data's bit crossing in eye-diagram mode. The amplitude of sine wave is set to 160 and 320 mV at two frequencies: 1 and 10 MHz. Their eye-diagrams and jitter histograms are recorded, and compared to those without added PJ. These results are analyzed in section 5.1.1.

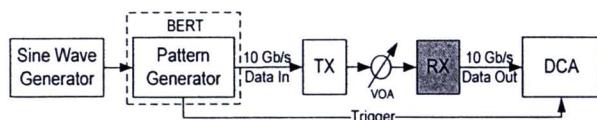


Fig.14: Block Diagram of Eye-diagram Measurement

4.1.2 Jitter Tolerance

To measure jitter tolerance as in Fig. 15, data and clock outputs are connected to ED for BER monitoring. The sine wave's frequency is fixed at one of these values: 0.7, 1, 2, 4, 10, 40 and 80 MHz. Its amplitude is gradually increased while maintaining BER better than 10^{-12} . The maximum p-p jitter amplitude is recorded. The same procedures are repeated at other frequencies. The results are plotted and compared with the standard SONET/SDH threshold [18] as shown in section 5.1.2. In addition, the jitter tolerance of BERT is also measured as 'loop back' reference by connecting PG directly to ED.

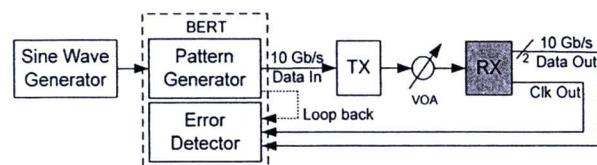


Fig.15: Block Diagram of Jitter Tolerance Measurement

4.2 DWDM Transmission Testbed

To demonstrate DWDM transmission, 3 wavelengths at 50 GHz spacing are transmitted through 40-km fiber, as described in section 4.2.1 Transmitter Side. Next, in section 4.2.2 Receiver Side, the 10 Gb/s data on center channel is dropped for eye-diagram analysis and BER

measurements. The block diagram and photo of DWDM testbed are shown in Fig. 16 and 17, respectively.

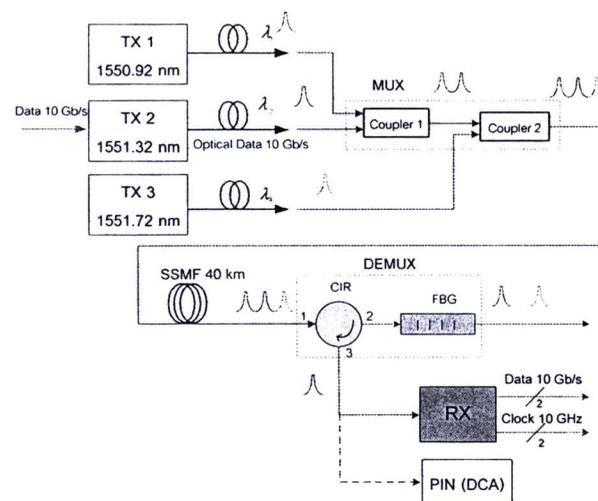


Fig.16: Block Diagram of DWDM Transmission

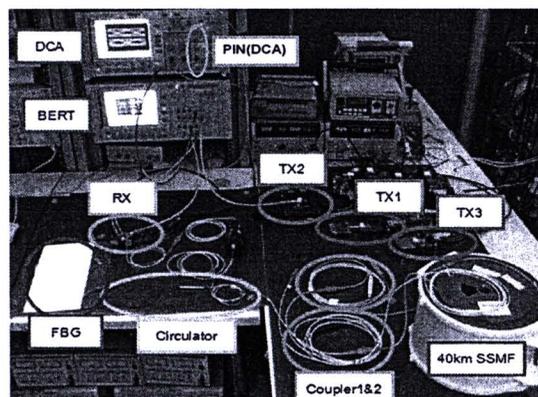


Fig.17: Photo of DWDM Experimental Testbed

4.2.1 Transmitter Side

Three transmitters (TX1, TX2 and TX3) using EML [16] have their wavelengths at 1550.92, 1551.32 and 1551.72 nm. Only the center channel is modulated with 10 Gb/s data due to a limited output from BERT, unlike in a real system where all wavelengths are modulated. However, in this case, the performance of optical receiver will not be significantly altered since these 3 wavelengths are farther apart as compared to their modulated spectra, shown later in Fig. 20. All wavelengths are multiplexed into one fiber via two 3-dB optical couplers. Their output powers after 2nd coupler are set to the same level with a total average power of +2.2 dBm measured by an inline optical power monitor at VOA.

The fiber is a single spool of 40 km long SSMF. Its total loss and length are measured by an Optical Time Domain Reflectometer (OTDR) = 7.77 dB and 39.9746 km, respectively, as shown in Fig. 18. Thus, the fiber attenuation is $(7.77/39.9746) = 0.1944$ dB/km at ~ 1550 nm wavelength. Its GVD is calculated from equation (3) to be 16.21 ps/(nm.km). This GVD will increase the rise and fall times of received signal.

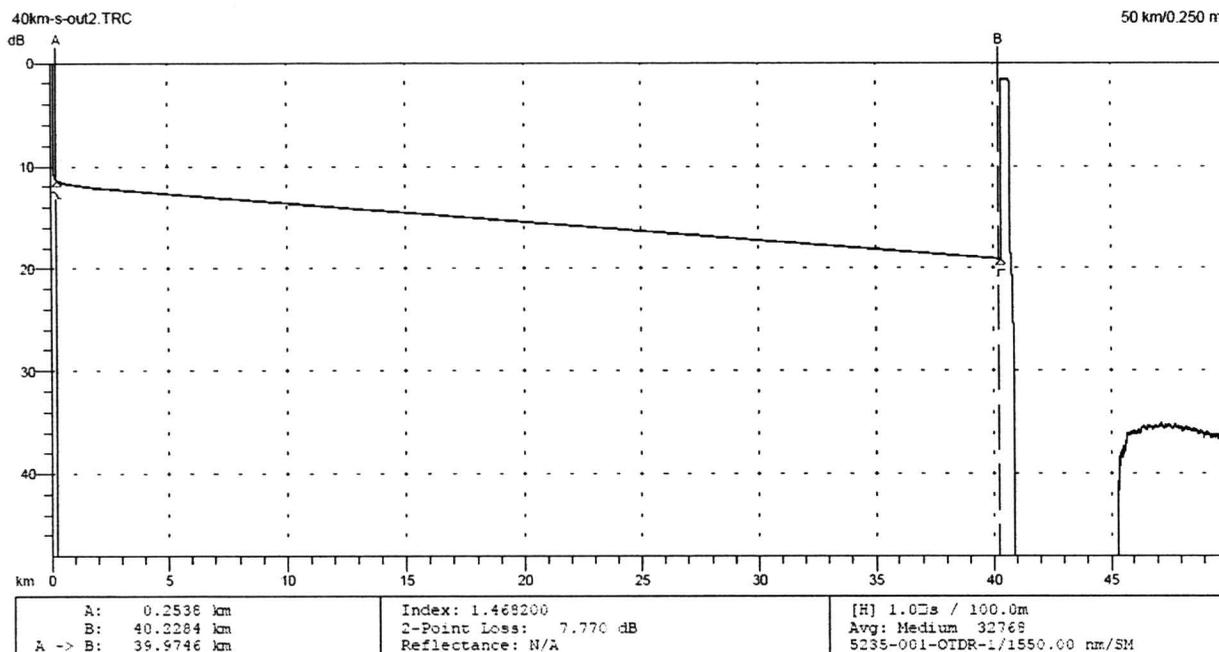


Fig.18: OTDR Measurement of 40-km SSMF

4.2.2 Receiver Side

After SSMF, the center wavelength is dropped by an optical de-multiplexer, which consists of one 3-port circulator and a Fiber Bragg Grating (FBG). The transmitted and reflected profiles of FBG are measured by an Optical Spectrum Analyzer (OSA) and shown as the upper and lower lines, respectively, in Fig. 19. The transmitted profile has its bottom power level at center wavelength 30 dB below those of other wavelengths. This FBG will then reflect the center wavelength and allow two neighbouring wavelengths to propagate through. Consequently, this de-multiplexer will drop only the center wavelength for data measurement.

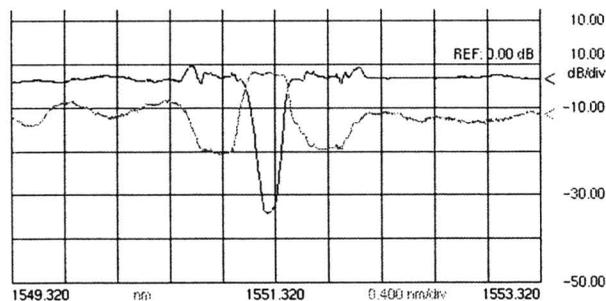


Fig.19: Transmitted and Reflected Profiles of FBG

In contrast, the reflected profile of FBG has its power level at center wavelength 16.9 dB higher than both sides. Therefore, the drop wavelength from de-multiplexer has its peak power 16.9 dB above those of two neighbouring

wavelengths, as shown in Fig. 20. This power difference indicates the amount of interchannel crosstalk that will cause a power penalty.

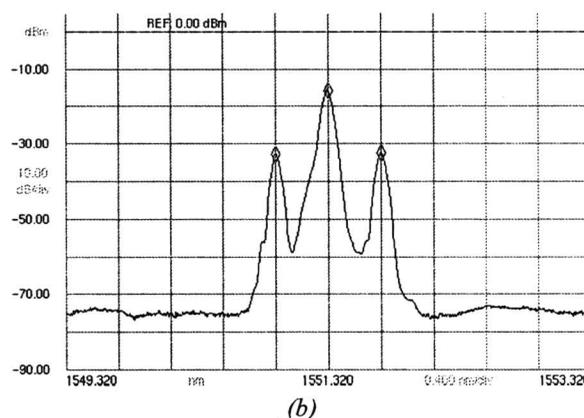


Fig.20: Spectrum of Received Optical Signal

After de-multiplexer, 10 Gb/s data is recovered by the receiver prototype. However, its output level does not vary proportionally with input power due to the data regeneration inside CDR circuit. As a result, the effects of both crosstalk and GVD cannot be clearly observed from the recovered eye-diagrams. For this particular reason, the PIN receiver Agilent 86105B module inside DCA, which has a linear characteristic detection, is temporary used instead for the observation of worsen eye-diagrams, but never for the performance comparison with receiver prototype. The photo of PIN receiver is shown in Fig. 21.

This PIN receiver has degraded over the years. Its current sensitivity is relatively worst at -6.3 dBm for 10^{-9} BER. Hence, its input power must be above that level for the PIN receiver to functionally perform optical-to-electrical data conversion.



Fig.21: PIN Receiver inside DCA

5. EXPERIMENTAL RESULTS

There are three main sets of experimental results: (1) jitter, (2) crosstalk and dispersion, and (3) BER, as described in section 5.1, 5.2 and 5.3, respectively.

5.1 Jitter Results

Two jitter results are jitter histograms of added PJ, and jitter tolerance of receiver prototype, as described in section 5.1.1 and 5.1.2, respectively.

5.1.1 Jitter Histogram Results

Fig. 22 shows the recovered 10 Gb/s eye-diagram from receiver prototype before adding PJ. The resulted jitter histogram inside a dash rectangle has only one Gaussian profile due to inherent RJ in this transmission system. This shape is in agreement with Fig. 3(a). The measured total p-p jitter and rms jitter are 0.1 UI_{p-p} and 0.013 UI_{rms} , respectively.

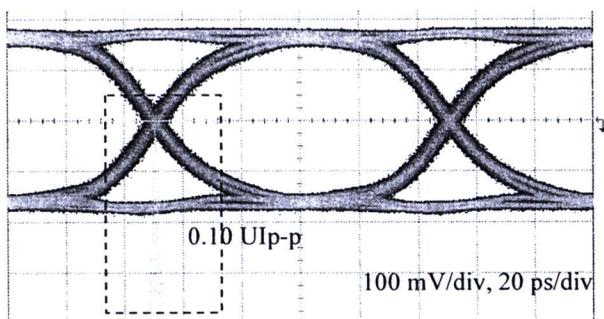


Fig.22: 10 Gb/s Eye-diagram with Jitter Histogram Before Adding Periodic Jitter

After adding PJ, at two different amplitudes and frequencies of sine wave, the resulted jitter histograms are compared in Table 2. Obviously, the jitter histograms become double Gaussian peaks due to a combination of

system RJ and added PJ. These results are in agreement with Fig. 3 (b). The total p-p jitters are also measured and reported in Table 2. The analysis of these p-p jitters indicates that the total jitter will be proportional to the applied amplitude of sine wave, which in agreement with equation (1). However, it will be inversely proportional to the applied frequency of sine wave. Due to the jitter transfer characteristic of chosen CDR chip, the measured total jitter will be reduced at those applied frequencies above 1 MHz.

Table 2: Jitter Histograms when the Voltage and Frequency of Input Sine Wave is Varied

	f = 1 MHz	f = 10 MHz
V = 320 mV	0.46 UIp-p	0.24 UIp-p
V = 160 mV	0.22 UIp-p	0.14 UIp-p

5.1.2 Jitter Tolerance Results

Fig. 23 shows the measured jitter tolerances at 10^{-12} BER of optical receiver prototype, 'RX' line, and BERT, 'Loop back' line. Since the 'RX' line is above the SONET standard [18], 'SONET MASK' line and is below the 'Loop back' line as expected, this receiver passes the standard jitter tolerance test. The explanation for higher tolerance at lower frequency is due to a slow change in phase such that the clock recovery circuit can rapidly complete its phase locking.

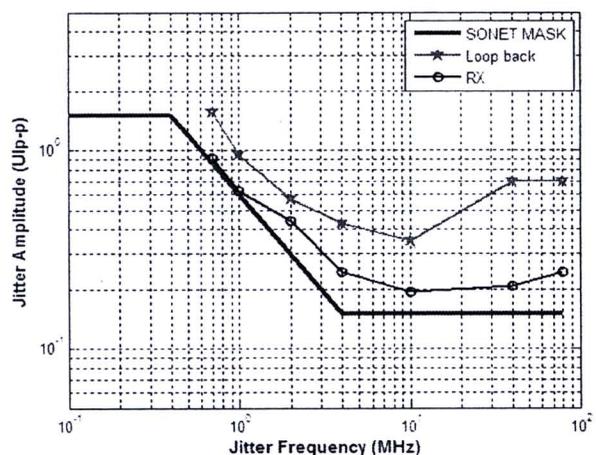


Fig.23: Comparison of Measured Jitter Tolerances

5.2 Crosstalk and Dispersion Results

The effects of interchannel crosstalk and GVD on eye-diagrams detected by PIN receiver and recovered by receiver prototype are described in section 5.2.1 and 5.2.2, respectively.

5.2.1 Eye-diagram from PIN receiver inside DCA

1) *Crosstalk Effect*: The transmission testbed is set as in Fig. 16, but without 40-km SSMF. The detected 10 Gb/s eye-diagram from PIN receiver with one wavelength and three wavelengths transmitted at the same average input power of -6 dBm are shown in Fig. 24(a) and Fig. 24(b), respectively.

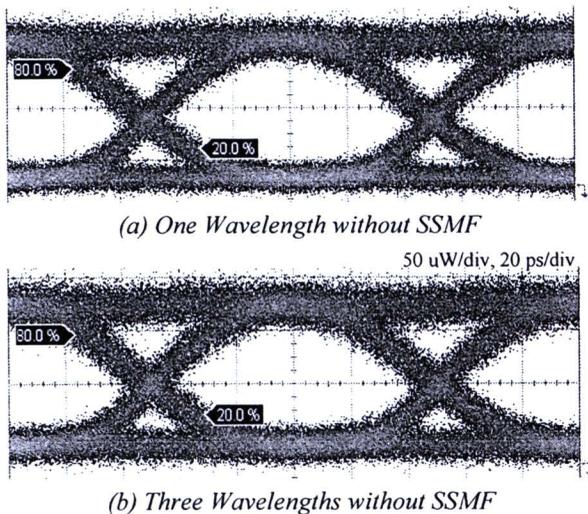


Fig.24: PIN's Eye-diagrams with 1 & 3 λ s

After a careful examination of the line thickness of bit '1' and '0' on eye-diagrams in Fig. 24, the crosstalk effect is very slightly shown as a thicker line in Fig. 24(b). This little difference is due to the very low interchannel crosstalk level of 16.9 dB from FBG.

2) *GVD Effect*: The testbed is set as in Fig.16, with only the center wavelength transmitted and thus without a de-multiplexer due to its insertion loss. The eye-diagrams of one wavelength without fiber and with 40-km SSMF are shown in Fig. 25(a) and Fig. 25(b), respectively.

Comparing the two eye-diagrams in Fig. 25, they clearly show an increase in the rise and fall times due to GVD impairment. The measured rise and fall times in Fig. 25(a) are 23.6 and 25.8 ps, respectively; whereas the rise and fall times in Fig. 25(b) are 53.8 and 54.2 ps, respectively. From these results, the GVD effect of 40-km SSMF can be analyzed as follows.

First, the GVD is calculated from equation (3) to be 16.21 ps/(nm.km). Then, the rise/fall time due to GVD is calculated from equation (2): $t_{GVD} = 16.21 \times 40 \times 0.06 = 38.904$ ps. The measured rise and fall times in Fig. 25(a) are the combined rise/fall time from transmitter and receiver, without GVD, as given in equation (4). Hence, the total rise and fall times of entire transmission system are recalculated from equation (4), using the calculated

t_{GVD} together with the measured rise and fall times in Fig. 25(a), = 45.50 and 46.68 ps, respectively. These numbers are slightly lower than the measured results at 53.8 and 54.2 ps, probably due to the inaccurate measurement of very distorted and noisy eye-diagram in Fig. 25(b).

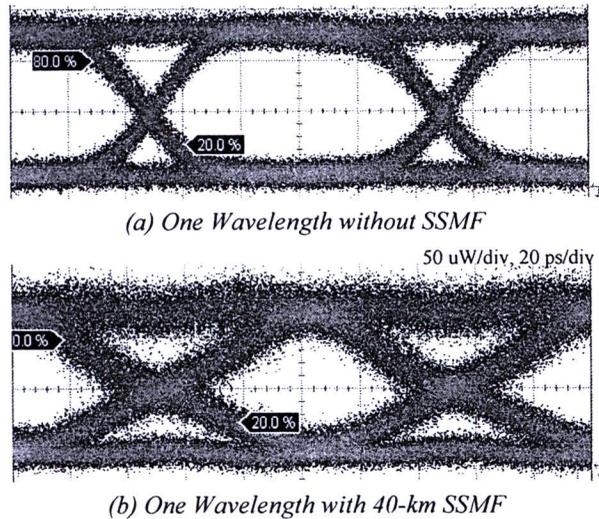


Fig.25: PIN's Eye-diagrams with & without SSMF

5.2.2 Eye-diagram from Optical Receiver Prototype

1) *Crosstalk Effect*: The testbed is set as in Fig. 16, without 40-km SSMF. The recovered 10 Gb/s eye-diagram by receiver prototype with one wavelength and three wavelengths transmitted at the same average input power of -26 dBm are shown in Fig. 26(a) and Fig. 26(b), respectively.

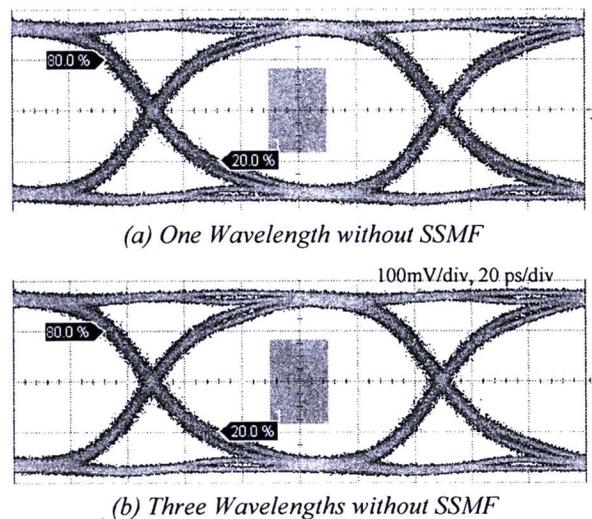
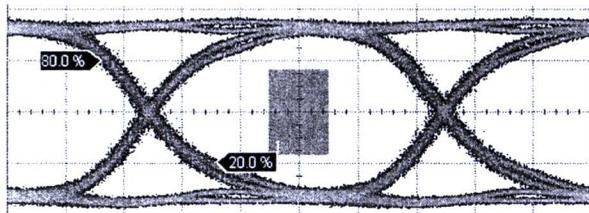


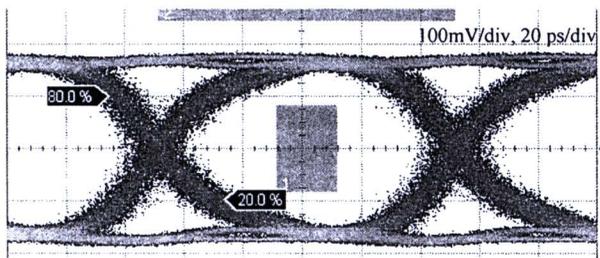
Fig.26: Prototype's Eye-diagrams with 1 & 3 λ s

A careful comparison between two eye-diagrams in Fig. 26 concludes that the crosstalk effect is unnoticeable due to the data regeneration of prototype. In the middle of eye-diagram, the bit '1' and '0' outputs are always fixed to the CML level, as described in section 3. Hence, this receiver can reduce the crosstalk impairment.

2) *GVD Effect*: The testbed is set as in Fig.16, with three wavelengths transmitted. The eye-diagrams of three wavelengths without fiber and with 40-km SSMF at the same averaged power of -26 dBm are shown in Fig. 27(a) and Fig. 27(b), respectively.



(a) Three Wavelengths without SSMF



(b) Three Wavelengths with 40-km SSMF

Fig. 27: Prototype's Eye-diagrams with & without SSMF

Comparing these two eye-diagrams in Fig. 27, they clearly show a broad and noisy spread of bit crossing due to GVD impairment. In the middle of eye-diagram, the bit '1' and '0' outputs are again fixed to the same CML levels. The measured rise and fall times are 31.6 and 33.3 ps, respectively. These numbers are much less than those from PIN receiver in Fig. 25 (b) due to data regeneration. For that reason, this receiver can significantly reduce the GVD impairment. The eye-diagram in Fig. 27 (b) also passes the standard STM-64/OC-192 data mask, shown as a gray rectangle at center as well as the upper and lower borders.

5.3 Bit Error Rate Results

Fig. 28 shows the BER performance of 10 Gb/s optical receiver prototype under four transmission cases: (1) only the center wavelength transmitted (*1wl*), (2) three wavelengths transmitted at 50 GHz spacing (*3wl 50GHz*), (3) the center wavelength transmitted over 40-km SSMF (*1wl+40km SSMF*), and (4) three wavelengths transmitted at 50 GHz spacing over 40-km SSMF (*3wl 50GHz+40km SSMF*). Evidently, the BER results will shift upward as the interchannel crosstalk and GVD effects are included in the experimental transmissions.

In order to determine the power penalty or path penalty of this prototype, first, the average received optical powers at 10^{-9} BER must be read from Fig. 27. According to those four transmission cases, their corresponding received powers are -26.4, -26.1, -25.7 and -25.3 dBm, respectively. Subsequently, the penalty is calculated as a power difference between a pair of those numbers, as follows.

1) *Crosstalk Effect*: The penalty between *3wl 50GHz* case and *1wl* case is $(-26.1 - (-26.4)) = 0.3$ dB, whereas the penalty between *3wl 50GHz+40km SSMF* case and *1wl+40km SSMF* case is $(-25.3 - (-25.7)) = 0.4$ dB. These two power penalties arise from the interchannel crosstalk impairment.

2) *GVD Effect*: Similarly, the penalty between *1wl+40km SSMF* case and *1wl* case is $(-25.7 - (-26.4)) = 0.7$ dB, whereas the penalty between *3wl 50GHz+40km SSMF* case and *3wl* case is $(-25.3 - (-26.1)) = 0.8$ dB. These two penalties arise from the GVD impairment. They both are lower than the 2 dB maximum penalty specified in the G.691 standard [7].

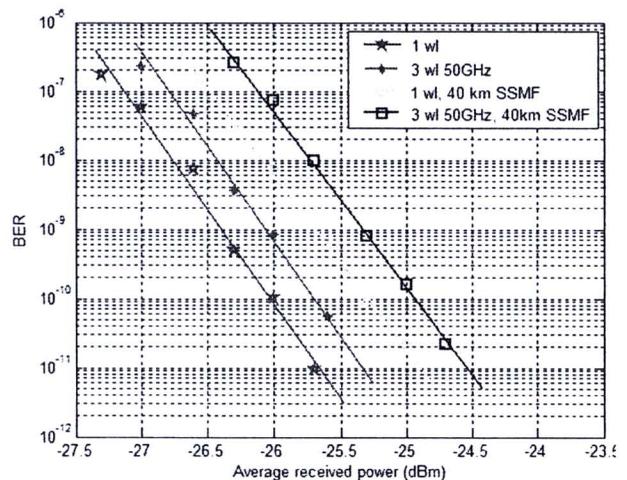


Fig.28: BER Plot of 10 Gb/s Optical Receiver Prototype

6. CONCLUSION

The design of 10 Gb/s optical receiver prototype using an APD with integrated TIA, a CDR chip with LA, and a 155.52 MHz reference clock is described. All components are successfully integrated onto the 4-layered FR-4 PCB. The two selected types of signal paths are differential microstrip line and single-ended CB-CPW. Their dimensions are optimally chosen for the lowest cost and matching impedance, according to the equations and the simulations from ADS and PolarSi8000 software. The prototype's performance has been evaluated under three impairments: jitter, interchannel crosstalk and GVD. The double Gaussian histograms of added PJ are analyzed to be proportional to amplitude and inversely proportional to frequency of applied sine wave. The jitter tolerance of prototype passes the SONET threshold with BER below 10^{-12} . The experimental testbed of three 50-GHz DWDM wavelengths transmitted over 40 km long SSMF is demonstrated. The effects of crosstalk and GVD on eye-diagrams are observed as the slightly thicker bit levels and the increase in rise and fall times, respectively. The measured rise and fall times are analyzed under GVD effect. The recovered eye-diagrams from prototype show that its design can reduce both crosstalk and dispersion effects. The BER performance of prototype are reported under four transmission cases, and the power penalty at

10^{-9} BER is determined to be 0.8 dB due to GVD effect. This value is within the standard limit of 2 dB.

7. ACKNOWLEDGEMENT

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Performance of 10 Gb/s Optical Receiver in 50-GHz DWDM Transmission over 40-km SSMF

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Abstract- This paper describes the design of our 10 Gb/s Avalanche Photo-Detector (APD) optical receiver and its overall performance in 50-GHz Dense Wavelength Division Multiplexing (DWDM) transmission over 40-km Standard Single Mode Fiber (SSMF). The experimental eye-diagram results show that our receiver can reduce the effects from channel crosstalk and fiber dispersion. In addition, its measured bit error rate (BER) is below 10^{-9} and the power penalty is within standard limit.

I. INTRODUCTION

Optical fiber communication has become very popular as compared to other systems because of its large bandwidth and low attenuation per distance. The main focus of research and development is to increase data rate of all components inside both optical transmitter and optical receiver up to multi Gb/s range. The current bit rate is 10 Gb/s for chip set [1] and 40 Gb/s for optical modulator [2].

Transmission capacity of WDM system is upgradable either by increasing the number of channels or decreasing the channel space between adjacent channels. For lower cost systems, the coarse WDM (CWDM) is normally used with channel spacing of 20 nm. Many transmitters and receivers are integrated into one CWDM transceiver [3]. In contrast, the DWDM system has many values of channel spacing: 200, 100, 50, 25, and 12.5 GHz (equivalent to 1.6, 0.8, 0.4, 0.2, and 0.1 nm at about 1550-nm wavelength) according to the ITU-T G.694.1 standard of spectral grids for WDM application. And, the spectral width of transmitter in DWDM is much narrower than that of CWDM. Most DWDM systems [4-5] use 100-GHz spacing, whereas the 50- and 25-GHz channel spacing [6] are chosen for a higher capacity system.

DWDM system is generally used in core networks with the transmission distance of standard values: 2, 15, 40, 80, 120 or 160 km. Thus, the distance between optical transmitter and receiver is another key performance. There are two problems in using a long SSMF (Standard Single Mode Fiber): fiber attenuation and Group Velocity Dispersion (GVD). First, the attenuation can be compensated by using optical amplifiers, such as Erbium Doped Fiber Amplifier (EDFA). Secondly, the dispersion that causes pulse spreading along distance can be mended by using Dispersion Compensation Fiber (DCF), which has a large negative dispersion. For the 10 Gb/s system over 40 km long SMF at 1550 nm wavelength, both EDFA and DCF will be used according to the ITU-T G.691 (standard of optical interfaces for single channel STM-64 and other SDH systems with optical amplifiers).

In this work, our designed 10 Gb/s optical receiver has been evaluated under 3 problems: jitter, crosstalk and dispersion. The jitter problem, which is the time variation of bit period, has already been experimented and reported in reference [7] according to SONET/SDH specification. Thus, this paper will demonstrate the crosstalk and dispersion effects using 50-GHz channel spacing and 40-km SSMF. This transmission condition is properly chosen from those described standard values and in agreement with the specification of 10 Gb/s optical transmitters used in our experimental testbed.

This paper is organized as follows. Section II explains the design of our 10 Gb/s optical receiver. The testbed of 50-GHz DWDM system over 40-km SSMF is described in section III. The experimental results are analyzed in section IV. Finally, the summary of this work is in section V.

II. DESIGN OF OPTICAL RECEIVER

In optical fiber communication, an optical receiver generally uses 2 types of semiconductor receiver: Positive-Intrinsic-Negative (PIN) and APD. PIN has lower noise level than APD. However, APD has a better sensitivity as well as larger output, and thus is more applicable for long distance applications. As a result, the APD is chosen in this design.

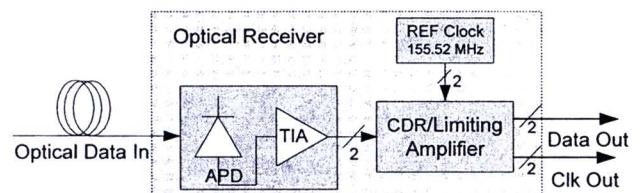


Figure 1. Components of the 10 Gb/s Optical Receiver Prototype

Our receiver prototype consists of 3 main components as shown in Fig. 1: APD with Trans-Impedance Amplifier (TIA) (R197A module from Cyoptics), Clock and Data Recovery (CDR) with Limiting Amplifier (MAX3991 chip from Maxim), and reference clock (CCPD-033 module from Crystek). After optical data is launched into the receiver, APD converts optical signal into photocurrent and then TIA converts it into a small voltage signal. Limiting Amplifier amplifies this signal up to constant voltage digital output and passes it through CDR. Clock output is recovered by phase lock loop, whereas Data output is regenerated by D-flip-flop and recovered clock. This CDR requires a reference clock signal at 1/64 (155.52 MHz) or 1/16 (622 MHz) of data rate, which is 9.9532 Gb/s (STM-64).

Main parameters of receiver prototype are shown in Table I and compared with 2 commercial optical transceivers (Finisar and Bookham) by considering only those parameters from receiver side. The data bit rate of prototype can be varied by changing frequency of reference clock. Both commercial transceivers do not have a fixed data bit rate because they receive reference clock from their host boards. The output level and rise/fall time are within the same ranges. This receiver prototype can detect a wide range of wavelength and has a high sensitivity of -25.3 dBm at 10^{-12} BER. Thus, it gives a larger dynamic range ($-2 - (-25.3) = 23.3$ dB). In addition, the maximum path penalty of receiver prototype is measured to be 0.8 dB (in section IV, C), which is less than the other two.

TABLE I
PARAMETER SUMMARIZATION AND COMPARISON

Electrical Characteristics	Receiver Prototype	Finisar [8]	Bookham [9]	Unit
- Data Bit Rate	9.95328	9.95-10.7	9.95-10.75	Gbps
- Different Output Voltage	575-725	340-850	360-770	mV
- Data Output Rise/Fall Time	30	38	24	ps
- Power Consumption	0.71(RX)	3.5 (TX&RX)	3.5 (TX&RX)	W
Optical Characteristics				
- Center Wavelength	1280-1610	1270-1600	1530-1560	nm
- Receiver Sensitivity @ 10^{-12}	-25.3	-24	-15.8	dBm
- Receiver Overload	-2	-7	-1	dBm
- Maximum Path Penalty @ 40km (20 ps/nm/km)	0.8	2 (@ 80 km)	2	dB

III. TESTBED OF 50-GHZ DWDM SYSTEM OVER 40-KM SSMF

To demonstrate 50-GHz DWDM transmission over 40-km SSMF, 3 fixed wavelengths at 50 GHz channel spacing are combined and propagate through 40 km long fiber. Its block diagram is shown in Fig. 2.

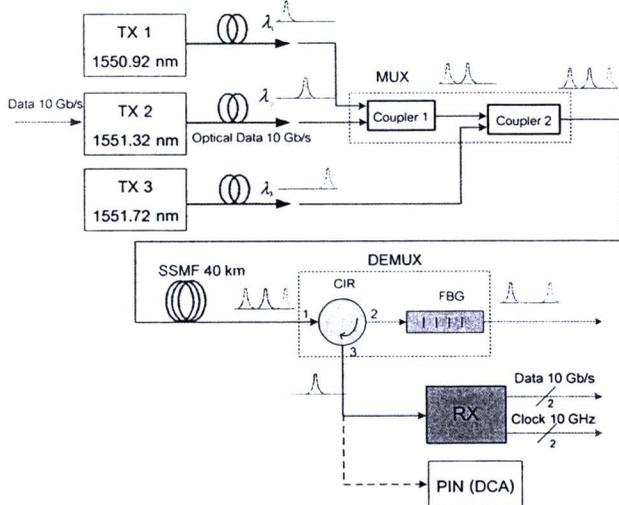


Figure 2. Block Diagram of 50-GHz DWDM system over 40-km SSMF

A. Transmitter Part

Three optical transmitters use the Electro-Absorption Modulation Integrated Lasers (EML) [10]. Their wavelengths are 1550.92 nm, 1551.32 nm and 1551.72 nm. Only the center wavelength is modulated with 10 Gb/s data due to a limited output from our Bit Error Rate Tester (BERT), unlike the real systems where all wavelengths are simultaneously modulated. However, in this case, the receiver's performance will not be significantly altered since these 3 wavelengths are farther apart as compared to their modulated spectral widths, as shown in Fig. 3(b). All wavelengths are multiplexed into one fiber via two 3-dB optical couplers. Their output powers after 2nd coupler are set to the same level with a total average power measured to be 2.2 dBm by an optical power monitor.

The transmission fiber is a single spool of 40 km long SSMF. Its total loss is measured to be 7.3 dB, thus the fiber attenuation (power loss per distance) is $(7.3/40) = 0.183$ dB/km. The GVD is about 20 ps/(nm.km). This dispersion will increase the rise and fall times of received data signal.

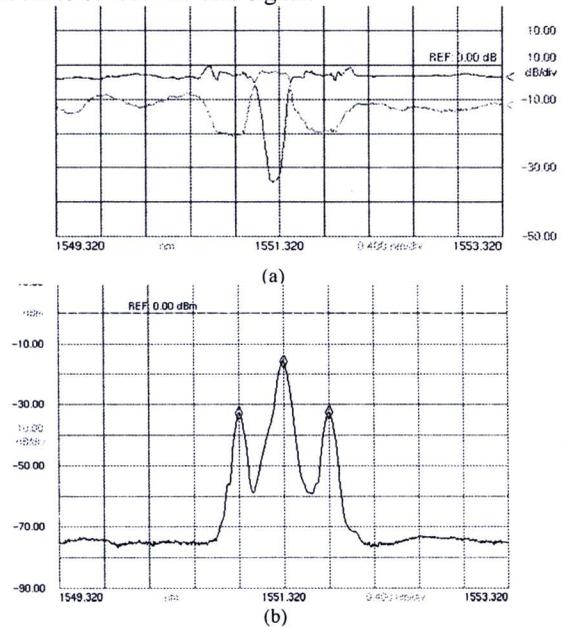


Figure 3. (a) Profile of FBG and (b) Spectrum of received signal

B. Receiver Part

After SSMF, the center wavelength is dropped by an optical de-multiplexer, which consists of 3-port optical circulator and a Fiber Bragg Grating (FBG). The transmitted and reflected profiles of FBG are shown as the upper and lower lines, respectively, in Fig. 3(a). The transmitted profile has its center wavelength 30 dB below other wavelengths. Thus, the output spectrum from FBG will eliminate center wavelength and transmit neighboring wavelengths. In contrast, the reflected profile has its center wavelength 16.9 dB higher than both sides. Therefore, the reflected output will have a higher power at center wavelength than neighboring wavelengths, as shown in Fig. 3(b).

Next, the reflected 10 Gb/s signal is detected by our receiver prototype to perform BER measurements. Due to the data regeneration from CDR, the output signal does not vary with its input power level. Thus, the effects of channel crosstalk and fiber dispersion will not be clearly seen from the eye diagrams of prototype's output. For this reason, the PIN receiver having a linear characteristic detection (inside Digital Communication Analyzer (DCA) 86150B module) is used instead to observe those worsened eye diagrams. But, this PIN receiver has a low sensitivity of -6.3 dBm at 10^{-9} BER, so its BER plot can not be measured as a comparison to our prototype. The pictures of PIN receiver in DCA and the prototype are shown in Fig. 4.

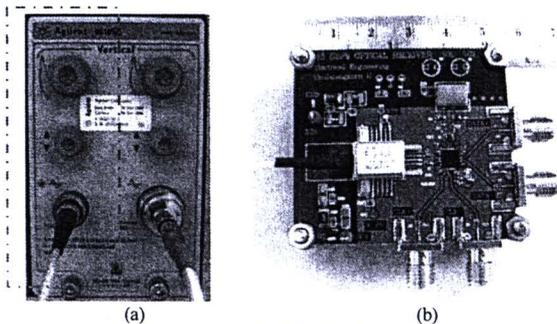


Figure 4. (a) PIN receiver inside DCA (b) optical receiver prototype

IV. EXPERIMENTAL RESULTS

A. Eye Diagram from PIN receiver inside DCA

1) *Crosstalk*: The testbed is set as in Fig.2, but without 40-km SSMF. The eye diagrams of one wavelength and three wavelengths at the same average optical power of -6 dBm are shown in Fig. 5(a) and Fig. 5(b), respectively.

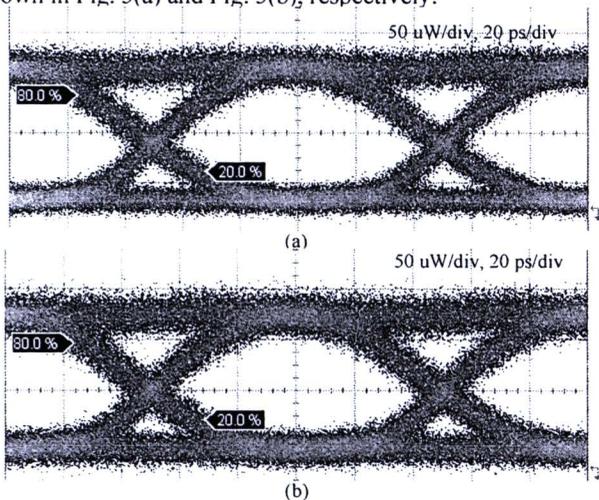


Figure 5. Eye diagram of PIN receiver (a) one wavelength (b) three wavelengths

After examining the line thickness of bit '1' and bit '0' on eye diagrams in Fig. 5, the crosstalk effect is very slightly shown as a thicker line in Fig. 5(b). This little difference is due to the low crosstalk level of 16.9 dB from FBG.

2) *Dispersion*: The testbed is set as in Fig.2, with only the center wavelength and without de-multiplexer due to its loss.

The eye diagrams of one wavelength without fiber and one wavelength with 40-km SSMF are shown in Fig. 6(a) and Fig. 6(b), respectively.

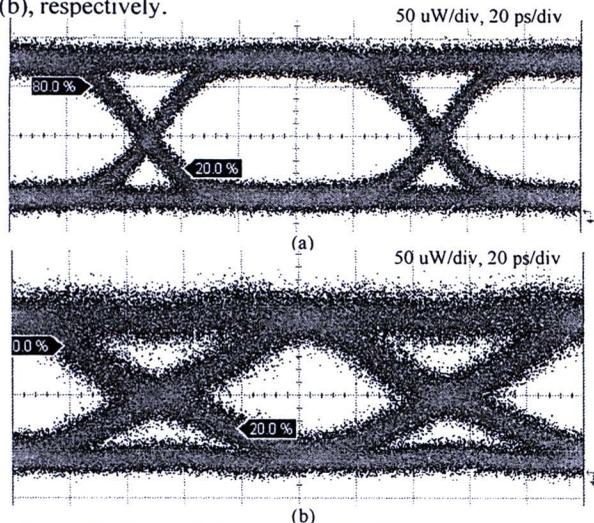


Figure 6. Eye diagram of PIN receiver (a) without SSMF (b) with 40-km SSMF

Comparing the eye diagrams in Fig. 6, they clearly show the dispersion effect as broadened signal. The measured rise and fall times in Fig. 6(a) are 23.6 and 25.8 ps, respectively, whereas the measured rise and fall times in Fig. 6(b) are 53.8 and 54.2 ps, respectively. From these results, the dispersion effect of 40-km SSMF is analyzed as follows.

First, the rise/fall time from dispersion effect is calculated from equation (1) to be $t_{GVD} = 20 \times 40 \times 0.06 = 48$ ps.

$$t_{GVD} \approx |D|L\sigma_{\lambda} \quad (1)$$

where t_{GVD} is the rise/fall time due to GVD, D is the fiber's GVD, L is the total length of fiber, and σ_{λ} is the 3-dB spectral width of transmitted wavelength.

Second, the measured rise and fall times in Fig. 6(a) are the combined rise/fall time from both the transmitter and receiver, without the fiber's GVD, as given in equation (2).

$$t_{sys} = \sqrt{(t_{tx}^2 + t_{rx}^2)} + t_{GVD} \quad (2)$$

where t_{sys} is the total rise/fall time of system, t_{tx} is the rise/fall time of transmitter, and t_{rx} is the rise/fall time of receiver.

Lastly, the total rise and fall times of whole transmission system are calculated from equation (2), using the calculated t_{GVD} as well as the measured rise and fall times in Fig. 6(a), to be 53.48 and 54.49 ps, respectively. These numbers are almost the same as the measured results in Fig. 6(b).

B. Eye Diagram from the Optical Receiver Prototype

1) *Crosstalk*: The eye diagram of 3 wavelengths without SSMF at an averaged power of -26 dBm is shown in Fig. 7. In the middle of eye diagram, bit '1' and bit '0' are fixed to upper and lower levels because of limiting amplifier. But, at the bit crossing of this eye diagram, it shows a little spread due to the crosstalk effect.

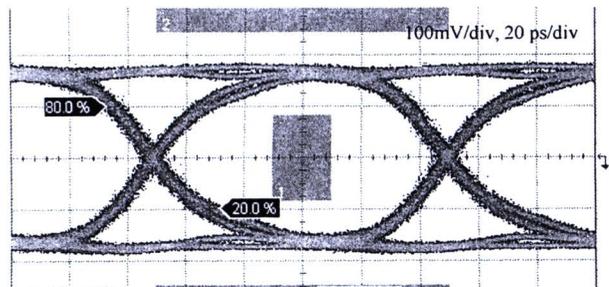


Figure 7. Eye diagram of receiver prototype, 3 wavelengths without SSMF

2) *Dispersion*: The eye diagram of 3 wavelengths with 40-km SSMF at the same averaged power of -26 dBm is shown in Fig. 8. The dispersion effect can be seen at the bit crossing. The measured rise and fall times are 31.6 and 33.3 ps, which are less than those from the PIN receiver (53.8 and 54.2 ps), because the CDR regenerates a new output shape.

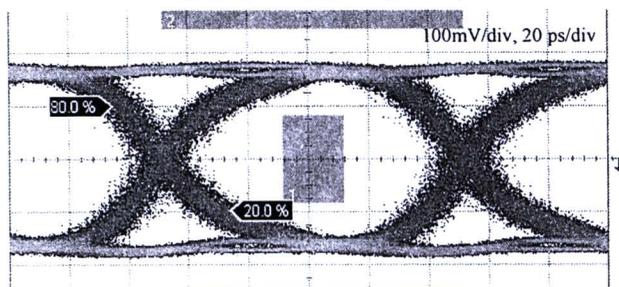


Figure 8. Eye diagram of receiver prototype, 3 wavelengths with 40-km SSMF

C. BER of Receiver Prototype

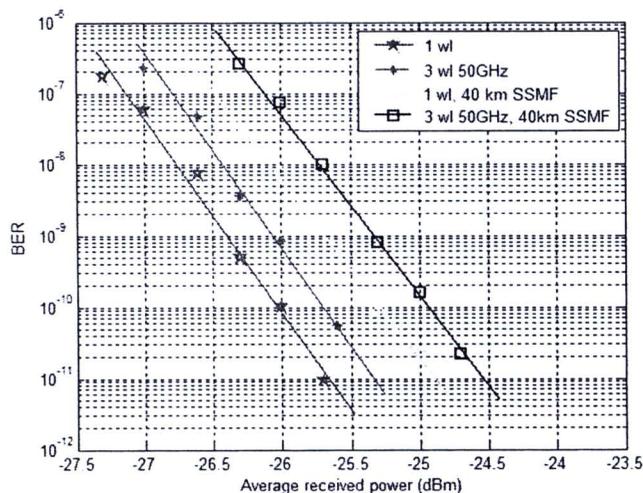


Figure 9. BER plot of receiver prototype

Fig. 9 shows the BER plot of our receiver prototype. The experiment was conducted in 4 cases: (1) one wavelength ($1wl$), (2) 3 wavelengths ($3wl\ 50GHz$), (3) one wavelength with 40-km SSMF ($1wl+40km\ SSMF$), and (4) 3 wavelength with 40-km SSMF ($3wl\ 50GHz+40km\ SSMF$). The average received powers at 10^{-9} BER of these 4 cases are -26.4, -26.1, -25.7 and -25.3 dBm, respectively. The power penalty of case $3wl\ 50GHz$

compared to case $1wl$ is 0.3 dB (-26.1-(-26.4)). The power penalty of case $3wl\ 50GHz+40km\ SSMF$ compared to case $1wl+40km\ SSMF$ is 0.4 dB (-25.3-(-25.7)). These two penalties arise from the crosstalk effect. Similarly, the power penalty of case $1wl+40km\ SSMF$ compared to case $1wl$ is 0.7 dB (-25.7-(-26.4)) and the power penalty of case $3wl\ 50GHz+40km\ SSMF$ compared to case $3wl$ is 0.8 dB (-25.3-(-26.1)), which is lower than the 2 dB maximum penalty of G.691 standard [11]. These later two penalties arise from the dispersion effect.

V. CONCLUSION

The design of 10 Gb/s optical receiver prototype using APD integrated with TIA, limiting Amplifier and CDR is described. The experimental testbed of 50-GHz DWDM transmission over 40-km SSMF is demonstrated. The effects of channel crosstalk and fiber dispersion on the measured eye diagrams are observed and analyzed. The BER results of optical receiver prototype are below 10^{-9} with the power penalty of 0.8 dB, which is within the standard limit of 2 dB.

ACKNOWLEDGMENT

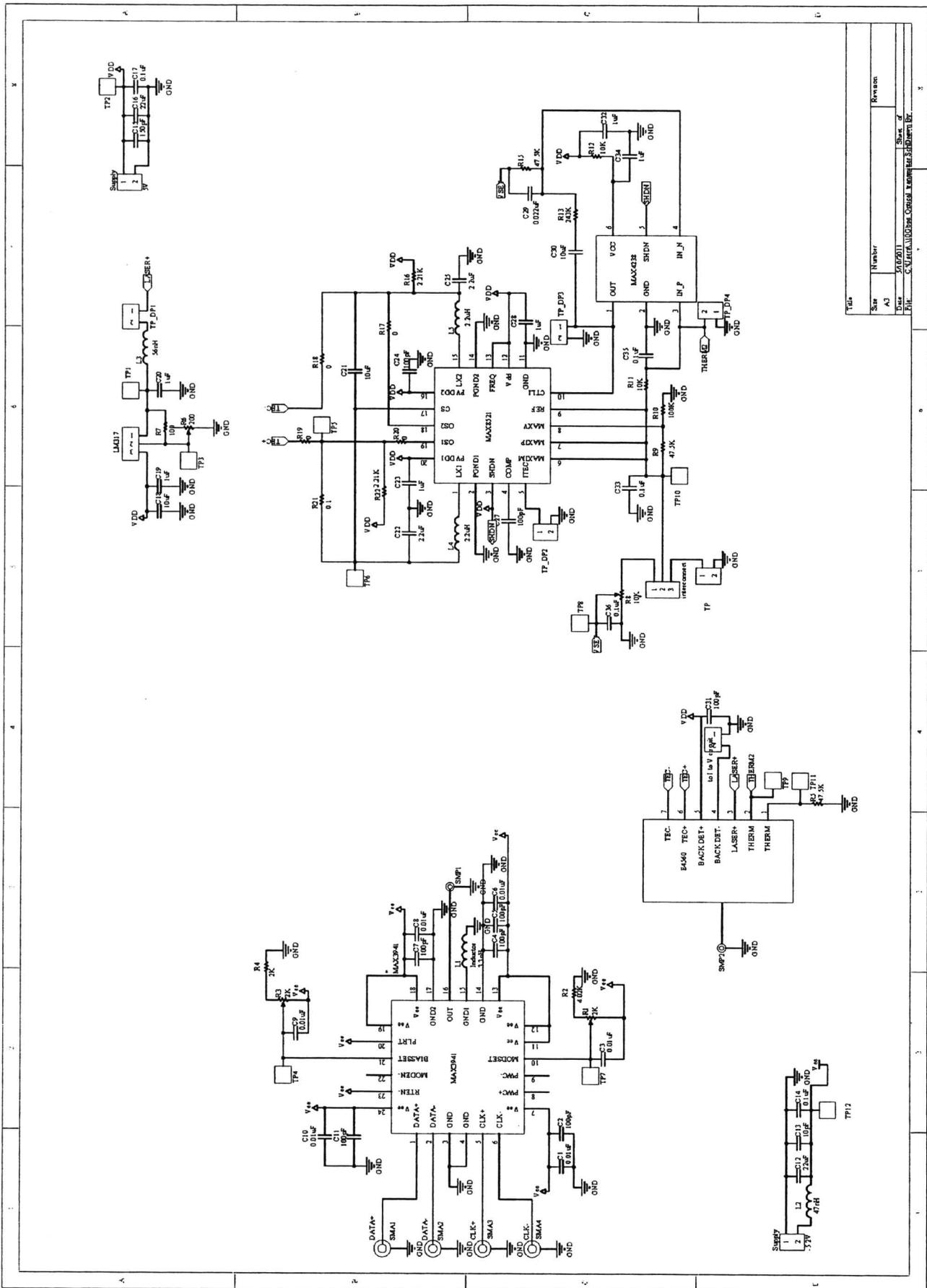
This work has been fully supported by Telecommunications Research and Industrial Development Institute (TRIDI), The National Telecommunications Commission (NTC).

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ภาคผนวก ข. Schematic ของตัวส่งสัญญาณทางแสงต้นแบบ

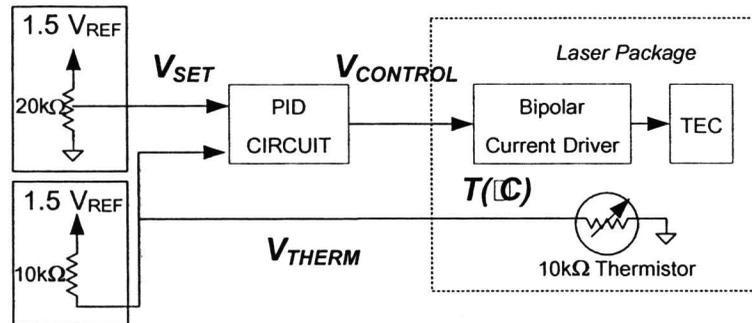
ลายวงจร Schematic ของตัวส่งสัญญาณทางแสงต้นแบบพร้อมระบบควบคุมอุณหภูมิใน
วิทยานิพนธ์ฉบับนี้เขียนลายวงจร โดยซอฟต์แวร์โปรแกรม Altium Designer



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ภาคผนวก ค. การอ้างอิงอุณหภูมิของเลเซอร์

อุณหภูมิของเลเซอร์ T ($^{\circ}C$) สามารถคำนวณได้จาก V_{THERM} ที่วัดได้จากเทอร์มิสเตอร์ขนาด $10\text{ k}\Omega$ ดังในรูปที่ ค.1 ตามสมการที่ (ค.1) โดยแสดงค่า V_{THERM} และอุณหภูมิของเลเซอร์ในแต่ละค่าความยาวคลื่น ตามมาตรฐานช่องสัญญาณ DWDM ITU-T 694.1 ดังตารางที่ ค.1



รูปที่ ค.1 แผนภาพการตั้งค่าและวัดอุณหภูมิของเลเซอร์

$$T(^{\circ}C) = \frac{\beta T_0}{T_0 \ln \left[\frac{V_{THERM}}{(V_{REF} - V_{THERM})} \right] + \beta} - 273.15 \tag{ค.1}$$

โดยที่ β คือค่าคงที่ของเทอร์มิสเตอร์เท่ากับ 4100, $T_0 = 298.15\text{ K}$ และ V_{REF} เท่ากับ 1.5 V

ตารางที่ ค.1 อุณหภูมิของเลเซอร์ที่คำนวณได้จากค่า V_{THERM} ของแต่ละความยาวคลื่น

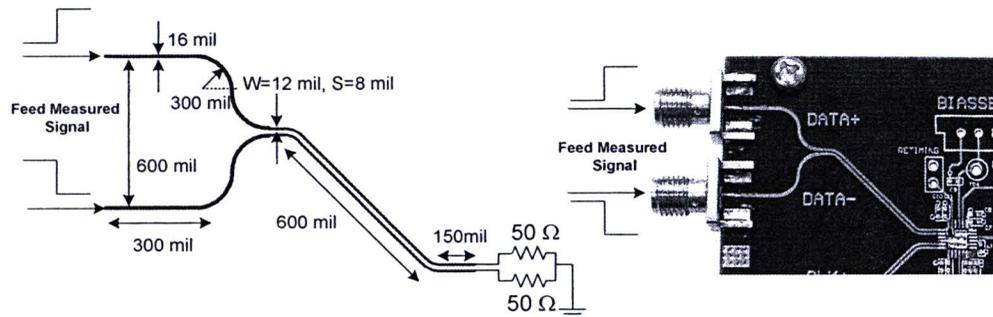
Channel (nm)	V_{SET}/V_{THERM} (V)	$V_{CONTROL}$ (V)	$T(^{\circ}C)$	Channel (nm)	V_{SET}/V_{THERM} (V)	$V_{CONTROL}$ (V)	$T(^{\circ}C)$
1550.72	0.908	1.31	17.0	1551.82	0.686	1.49	29.8
1550.82	0.887	1.33	18.2	1551.92	0.666	1.51	31.1
1550.92	0.865	1.34	19.5	1552.02	0.645	1.52	32.4
1551.02	0.844	1.36	20.6	1552.12	0.626	1.54	33.5
1551.12	0.825	1.38	21.7	1552.22	0.609	1.55	34.6
1551.22	0.806	1.40	22.8	1552.32	0.592	1.56	35.7
1551.32	0.785	1.41	24.0	1552.42	0.575	1.57	36.8
1551.42	0.764	1.43	25.3	1552.52	0.555	1.58	38.1
1551.52	0.743	1.45	26.5	1552.62	0.537	1.59	39.4
1551.62	0.723	1.47	27.6	1552.72	0.52	1.61	40.6
1551.72	0.704	1.48	28.8				

ภาคผนวก ง. การวัดค่าอิมพีแดนซ์คุณลักษณะด้วยเครื่อง TDR

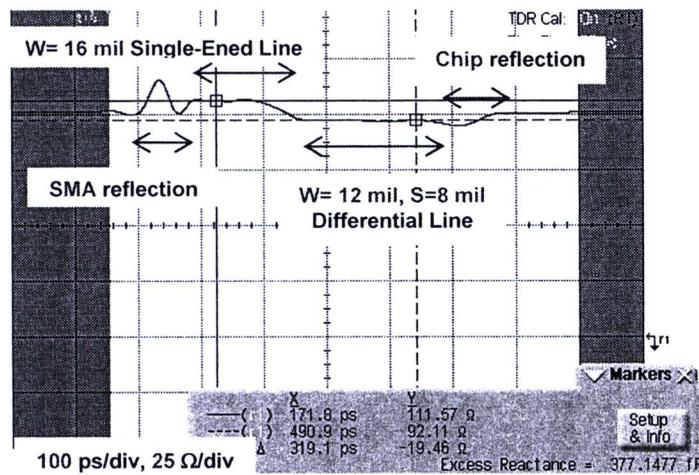
การวัดค่าอิมพีแดนซ์คุณลักษณะของเส้นสัญญาณแบบผลต่าง (Z_{DIFF}) และแบบเดี่ยว (Z_0) ใช้เครื่อง TDR ของบริษัท Agilent รุ่น 54754A [54] ในการวัดทดสอบ โดยมีรายละเอียดในหัวข้อที่ ง.1 และ ง.2 ตามลำดับ

ง.1 การวัดค่าอิมพีแดนซ์คุณลักษณะของเส้นสัญญาณแบบผลต่าง

การวัดค่า Z_{DIFF} ของเส้นสัญญาณไมโครสตริปแบบผลต่างจะต้องบัดกรีโหลด ซึ่งเป็นชิปตัวต้านทาน 50Ω ขนาด 0402 จำนวน 2 ตัว ขนานลงกราวด์ไว้ทั้งคู่ดังรูปที่ ง.1 เพื่อที่จะทำให้เครื่อง TDR เห็นค่าอิมพีแดนซ์ที่ปลายทางเป็น 100Ω ซึ่งเป็นการลดการสะท้อนของสัญญาณที่ปลายทางกรณี Open Circuit ไว้ โดยมีผลการวัดแสดงดังรูปที่ ง.2



รูปที่ ง.1 การเชื่อมต่อเส้นสัญญาณแบบผลต่างกับโหลด



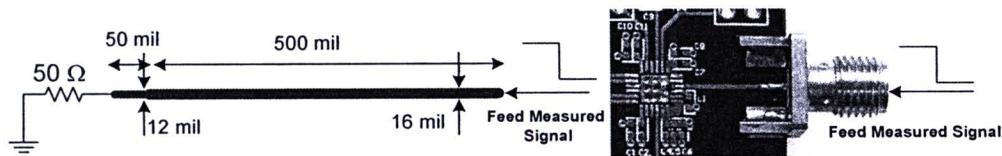
รูปที่ ง.2 ผลการวัดค่าอิมพีแดนซ์ของเส้นสัญญาณแบบผลต่าง

เมื่อป้อนสัญญาณแบบผลต่างจากเครื่อง TDR ไปยังเส้นสัญญาณที่ได้ออกแบบพบค่าอิมพีแดนซ์ของเส้นสัญญาณมีลักษณะดังรูปที่ ง.2 ซึ่งแบ่งออกเป็น 4 ส่วน คือ (1) หัวต่อ SMA เมื่อสัญญาณเดินทางผ่านหัวต่อจะมีการสะท้อนของสัญญาณเกิดขึ้น เนื่องจากความไม่ต่อเนื่องของอิมพีแดนซ์ตาม datasheet ของหัวต่อ [46], (2) เส้นสัญญาณแบบเดี่ยวที่เดินทางขนานเข้ามาสองเส้นวัดค่าอิมพีแดนซ์ได้ 111.57Ω ซึ่งมีค่าประมาณ 2 เท่าของ Z_0 จากนั้นค่าอิมพีแดนซ์จะค่อยๆ

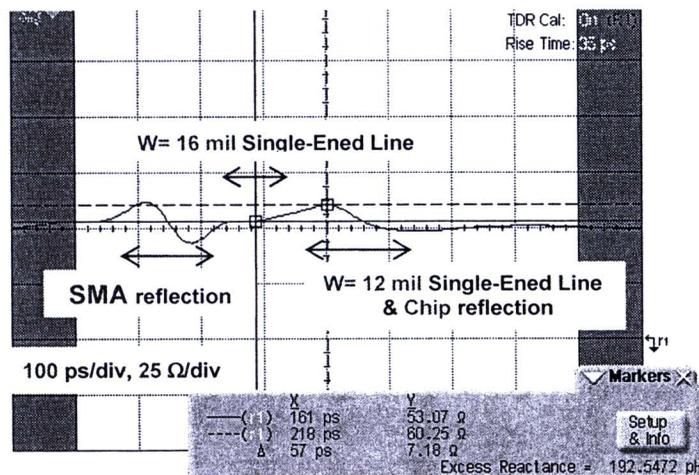
ลดลงเนื่องจากระยะห่างขอบเส้นสัญญาณ (S) แคบลงดังสมการที่ (2.16) เพื่อเข้าสู่เส้นสัญญาณในส่วนถัดไป, (3) เส้นสัญญาณแบบผลต่าง ซึ่งมีค่าอิมพีแดนซ์เป็นแบบผลต่าง (Z_{DIFF}) วัดค่าได้ 92.11 Ω , และ (4) Pad สำหรับวางชิป จะมีการสะท้อนของสัญญาณเกิดขึ้นเล็กน้อยและมีค่าอิมพีแดนซ์ค่อยๆเพิ่มเข้าสู่ 100 Ω ตามโหลดชิปตัวด้านทานที่บัดกรีไว้

ง.2 การวัดค่าอิมพีแดนซ์คุณลักษณะของเส้นสัญญาณแบบเดี่ยว

การวัดค่า Z_0 ของเส้นสัญญาณไมโครสตริปแบบเดี่ยว จะต้องบัดกรีโหลดซึ่งเป็นชิปตัวด้านทาน 50 Ω ขนาด 0402 ลงกราวด์ไว้ที่ปลายทางด้านรูปที่ ง.3 เพื่อที่จะทำให้เครื่อง TDR เห็นค่าอิมพีแดนซ์ที่ปลายทางเป็น 50 Ω ซึ่งเป็นการลดผลการสะท้อนดังที่ได้กล่าวไปในหัวข้อที่ ง.1 โดยมีผลการวัดแสดงดังรูปที่ ง.4



รูปที่ ง.3 การเชื่อมต่อเส้นสัญญาณแบบผลเดียวกับโหลด



รูปที่ ง.4 ผลการวัดค่าอิมพีแดนซ์ของเส้นสัญญาณแบบเดี่ยว

เมื่อป้อนสัญญาณแบบผลต่างจากเครื่อง TDR ไปยังเส้นสัญญาณแบบเดี่ยวที่ได้ออกแบบพบว่าค่าอิมพีแดนซ์ของเส้นสัญญาณมีลักษณะดังรูปที่ ง.4 ซึ่งแบ่งออกเป็น 3 ส่วน คือ (1) หัวต่อ SMA เมื่อสัญญาณเดินทางผ่านหัวต่อจะมีการสะท้อนของสัญญาณเกิดขึ้น เนื่องจากความไม่ต่อเนื่องของอิมพีแดนซ์ตาม datasheet ของหัวต่อ [46], (2) เส้นสัญญาณแบบเดี่ยวกว้าง 16 mil ยาว 500 mil วัดค่า Z_0 ได้ 53.07 Ω จากนั้นเส้นสัญญาณจะมีขนาดเล็กลงตามขนาด pad สำหรับวางชิปซึ่งเป็นเส้นสัญญาณในส่วนถัดไป, และ (3) เส้นสัญญาณแบบเดี่ยวกว้าง 12 mil ยาว 50 mil ทำให้ค่า Z_0 เพิ่มมากวัดได้ 60.25 Ω จากนั้นจึงค่อยๆ ลดค่าเข้าสู่ 50 Ω ตามชิปตัวด้านทานที่บัดกรีไว้ที่ปลายทาง

ประวัติผู้เขียนวิทยานิพนธ์

นายจิรวุฒิ อัครานูชาติ เกิดวันที่ 9 กันยายน พ.ศ. 2529 ที่จังหวัดสุโขทัย เข้าศึกษาในหลักสูตรวิศวกรรมศาสตรบัณฑิต คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย ในปีการศึกษา 2548 สำเร็จการศึกษาวิศวกรรมศาสตรบัณฑิต สาขาวิชาวิศวกรรมไฟฟ้า ภาควิชาวิศวกรรมไฟฟ้า คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย ในปีการศึกษา 2551 ต่อจากนั้นได้เข้าศึกษาต่อในหลักสูตรวิศวกรรมศาสตรมหาบัณฑิต คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย ในปีการศึกษา 2552 และสำเร็จการศึกษาวิศวกรรมศาสตรมหาบัณฑิต สาขาวิชาวิศวกรรมไฟฟ้า ภาควิชาวิศวกรรมไฟฟ้า คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย ในปีการศึกษา 2553



