Widely-Tunable Electroabsorption-Modulated Sampled Grating DBR Laser Integrated with Semiconductor Optical Amplifier

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Abstract: We report on a sampled grating DBR laser monolithically integrated with an electroabsorption modulator and semiconductor optical amplifier. A fiber coupled time-averaged power in excess of 3 dBm across a 40 nm tuning range and 2.5 Gb/s transmission over 200 km of standard fiber are achieved.

OCIS codes: (250.5300) Photonic integrated circuits; (060.2330) Fiber optics communications

1. Introduction

Tunable lasers are desired for optical networking applications ranging from one time wavelength provisioning and sparing to dynamic wavelength provisioning in re-configurable optical add/drop multiplexers, photonic cross-connects, and all-optical regenerators. Several tunable laser technologies with direct or integrated modulation (≥2.5 Gb/s) have been demonstrated [1-4]. Among those only the Sampled Grating Distributed Bragg Reflector (SG-DBR) laser architecture combines the advantages of wide tuning range, high output power, simplicity for integration with other components [4-6], and high reliability [7]. In this paper we report on a tunable 2.5 Gb/s transmitter based on a SG-DBR laser monolithically integrated with a semiconductor optical amplifier (SOA), and an electro-absorption modulator (EA) modulator, and demonstrate transmission over distances required in long-reach metro applications.

2. Device design and fabrication

As illustrated in Fig. 1, the device consists of a four-section SG-DBR laser, an SOA, and an EA modulator, all integrated on the same InP chip. The SOA compensates on-state modulator loss and cavity losses caused by free carrier absorption in the tuning sections and allows power leveling with insignificant wavelength deviation. The integration of the laser and SOA active regions with the tuning and modulator sections of the device has been accomplished by using an offset quantum-well structure [4]. In this simple integration technology the active region of the modulator uses the same bulk quaternary waveguide as the tuning sections of the laser. The Franz-Keldysh effect in the bulk waveguide material provides for larger spectral bandwidth as compared to the quantum-confined Stark effect. The composition of the bulk waveguide can be optimized to achieve high tuning efficiency for the laser and a target extinction ratio over the required wide spectral bandwidth for the modulator. An angled waveguide and wide-band anti-reflection coating at the output of the device were used to suppress the optical feedback to the SGDBR laser.

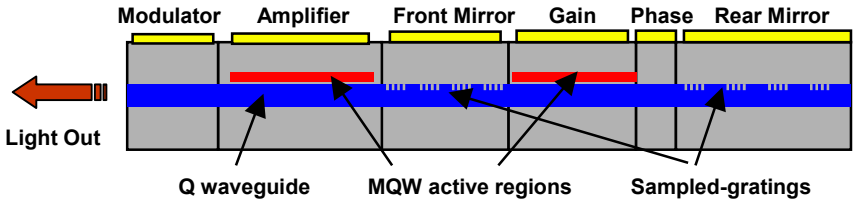

Fig. 1. Schematic of SG-DBR laser integrated with SOA and EA modulator.

3. Results and discussion

The device was packaged in a cooled butterfly package with a co-planar RF input. The package was mounted into a transmitter assembly with *dc* current and voltage drivers. The ITU channel selection is done using a look up table for the laser and SOA currents and the *dc* bias voltage for the modulator. More than 100 consecutive 50 GHz spaced ITU channels with fiber coupled output powers > 10 mW and SMSR greater than 40 dB were demonstrated for $I_{gain} = I_{SOA} = 150$ mA and $V_{mod} = 0$ V (Fig. 2a). Relative intensity noise is less than –145 dB/Hz and unmodulated time-average linewidth is below 20 MHz across the tuning range.

The extinction ratio (ER) characteristics of EA-modulators are strongly dependent on the detuning between the lasing and absorption-edge wavelengths. To provide uniform *RF* ER over a wide spectral bandwidth, the dc bias on the modulator section has been adjusted for each channel. Power leveling was accomplished by adjusting SOA current in the range of 40-100 mA. Time-averaged power > 3 dBm and *RF* ER > 10 dB was simultaneously obtained across the tuning range with 3 V peak-to-peak modulation (Fig. 2b).

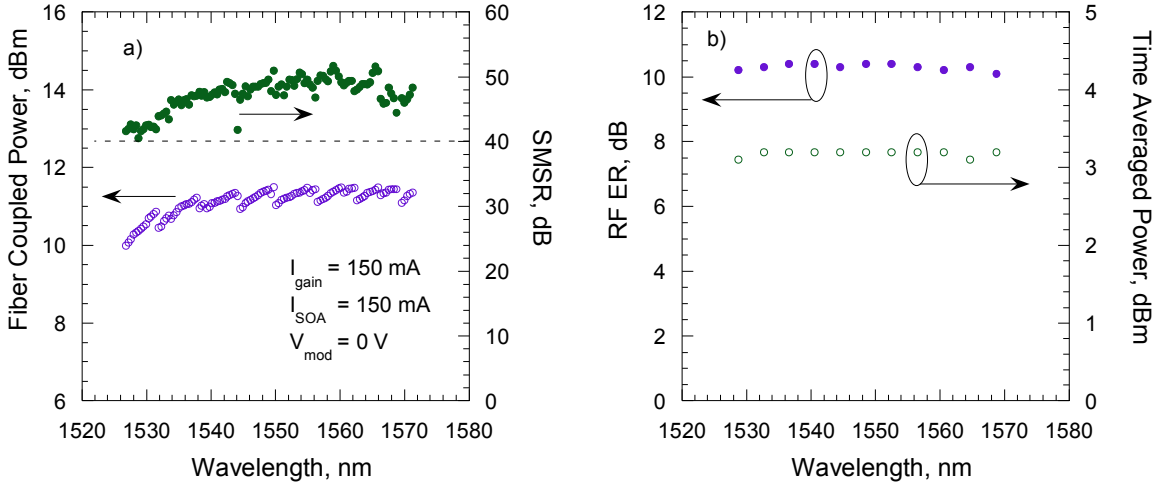

Fig. 2. a) Fiber coupled power and SMSR across the tuning range. b) *RF* extinction ratio and fiber coupled time averaged optical power vs. wavelength for a fixed 3V pk-pk rf drive voltage.

The fiber transmission experiments were performed using integrated SGDBR-SOA-EA modulator chip mounted on RF ceramic carrier. Bit error rate characteristics for three representative channels are shown in Fig. 3. Error-free transmission has been demonstrated for 200 km of standard single mode fiber. The dispersion penalty is < 0.3 dB at 1560 nm and <1.5 dB at 1530 nm. Further optimization of EA modulator operating parameters should result in lower dispersion penalty at short wavelength range.

4. Summary

In summary, we have demonstrated a widely-tunable, 2.5 Gb/s transmitter based on a SG-DBR laser monolithically integrated with a SOA and EA modulator. Time-averaged powers in excess of 3 dBm and *RF* extinction ratio > 10 dB across a 40 nm tuning range have been achieved. Error-free transmission at 2.5 Gb/s has been demonstrated for 200 km of standard single mode fiber.

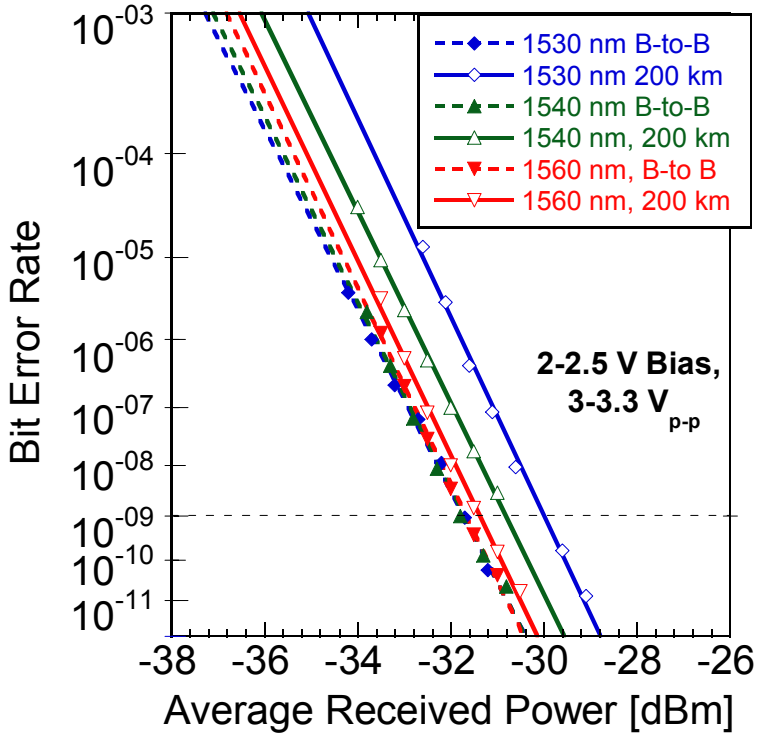

Fig. 3. Bit error rate curves for 0 and 200 km of standard single-mode fiber spans for three different wavelengths (2.5 Gb/s NRZ, 2^{31}-1 PRBS).

5. References

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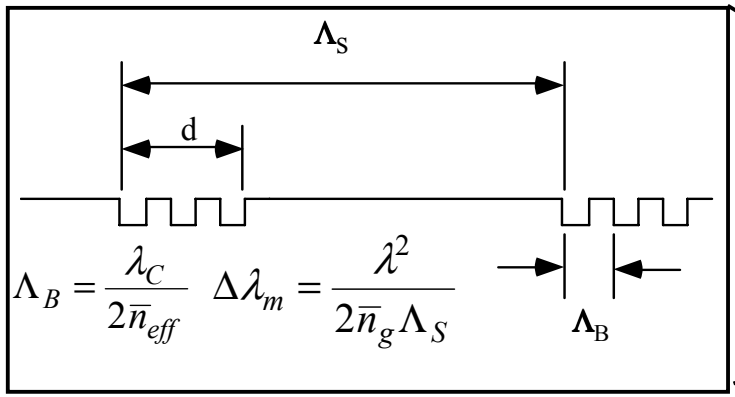
Outline

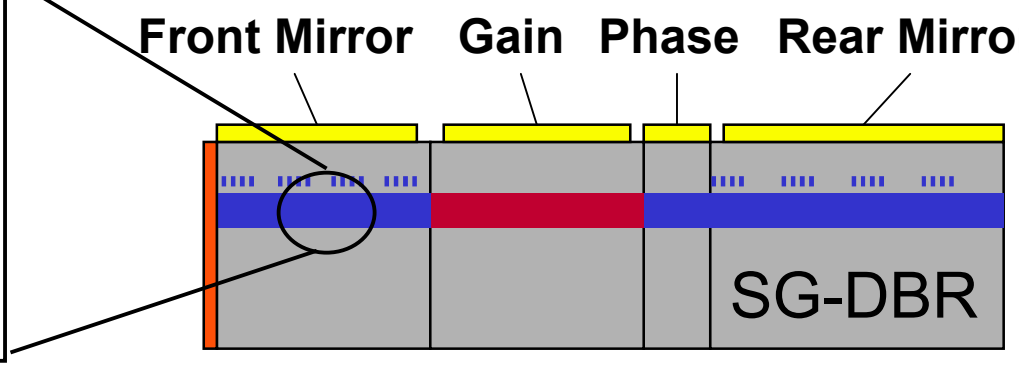
- **Introduction to Widely-Tunable SG-DBR Lasers**
  - System requirements
- **Device design**
  - SG-DBR Lasers: Theory of Operation
  - Integration with other components
- **CW operation SGDBR-SOA-EAM**
- **High-speed performance**
- **Summary**

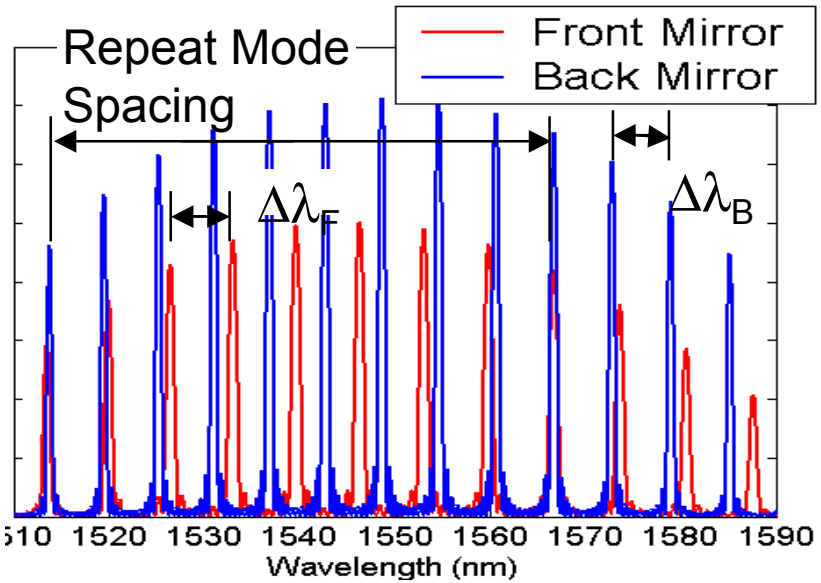
Requirements for Tunable Lasers

- **Output Power**
  - External Mod. – 10-20 mW
  - Integrated Mod. – 0-5 dBm
- **Tuning Range**
  - Replacement – 8-32 nm
  - Enabling – >32 nm
- **Tuning Speed**
  - Sparing – 1 sec
  - Restoration – <10 ms
  - Packet Switching – <10 ns
- **Wavelength Control**
  - 100 GHz – ±5 GHz
  - 50 GHz – ±3 GHz
  - 25 GHz – ±1 GHz

Sampled Grating Mirror Design







5-10X Tuning Range of DBR

Reliable, Manufacturable InP Technology

Can Cover C band, L band or C + L

Easily Integrates Monolithically with Other Components (e.g. EAM, SOA)

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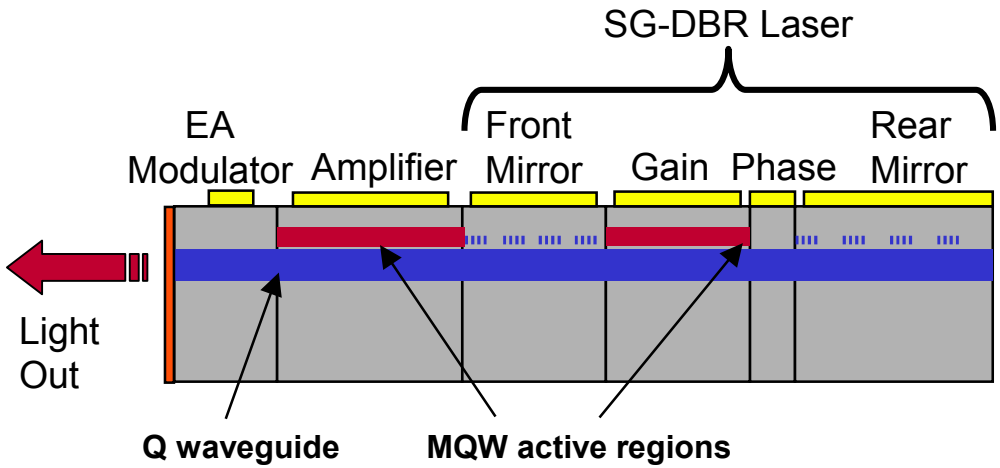
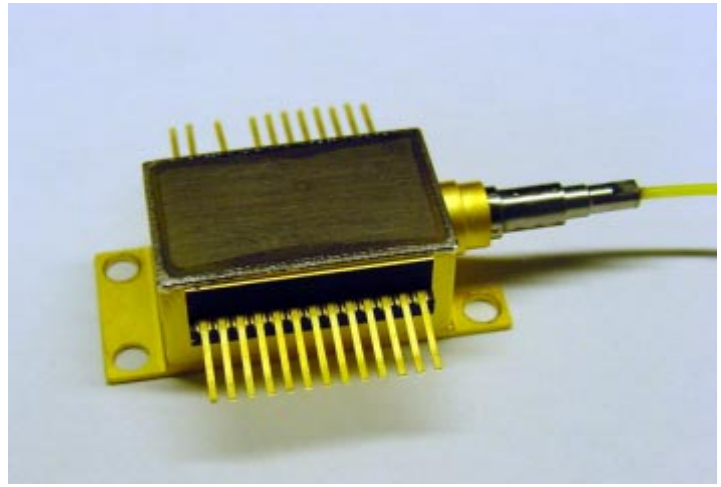
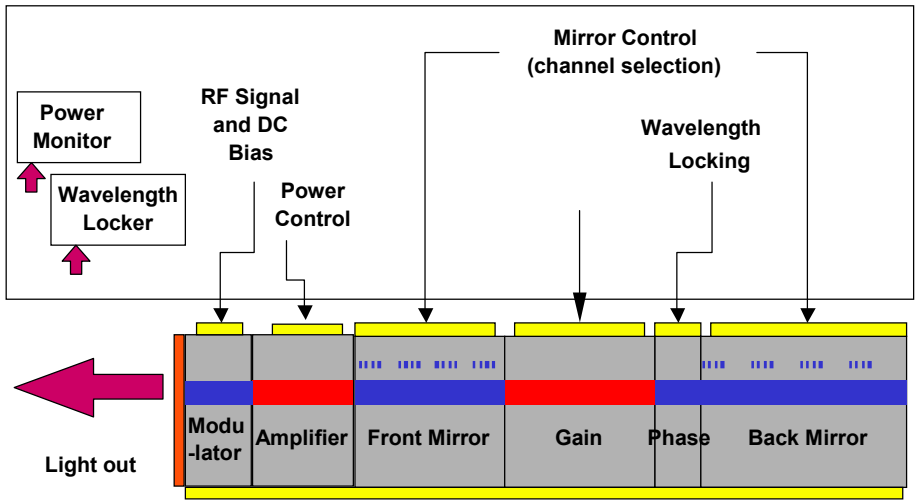
Device design and integration technology





- Monolithic InP chip/ same material structure and process as for SGDBR alone
- Waveguide common to SGDBR, SOA , and EA modulator
- Optimized for *RF ER* and chirp over 40 nm tuning range, and FM efficiency of the tuning sections
- SOA Breaks Power/Tuning Range Tradeoff + VOA function

TEMLA – Tunable Electroabsorption Modulated Laser Assembly



- Close loop control:
  - ✓ Power
  - ✓ Wavelength
  - ✓ Mirror control
  - ✓ Temperature
- Modulator driver:
  - ✓ V_{pp}
  - ✓ V_{dc}

- Compact footprint and industry standard pinout
- Microprocessor based control system
- Integral wave-locker (50 GHz etalon)
- Tuning of the laser and modulator driver for the desired channel < 10 mS
- VOA
  - Blanked output power –30 dBm
  - VOA dynamic range > 10 dB

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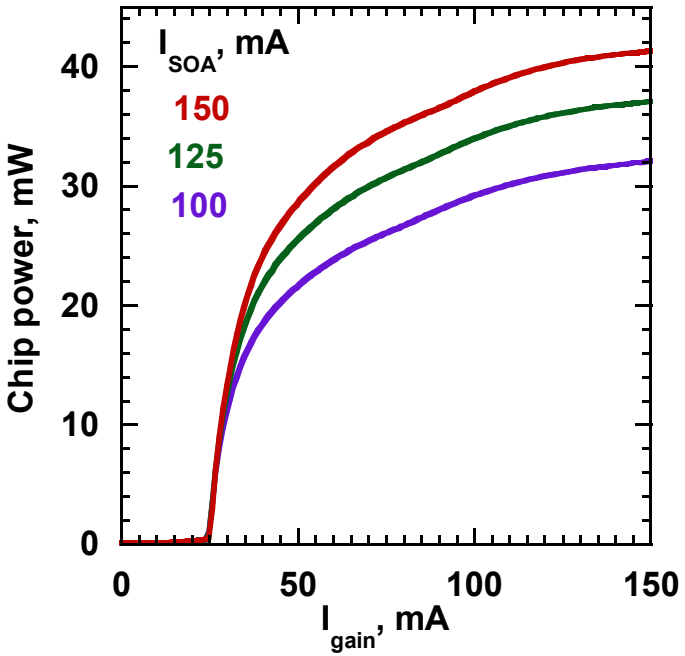
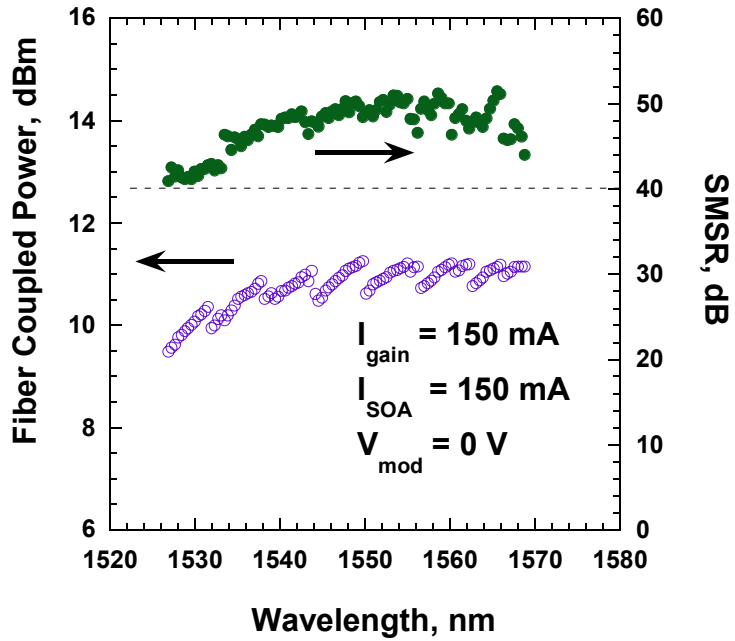
CW Performance of SGDBR-SOA-EAM





- >100 50 GHz ITU Channels
- Fiber coupled power > 10 dBm
- SMSR > 40 dB

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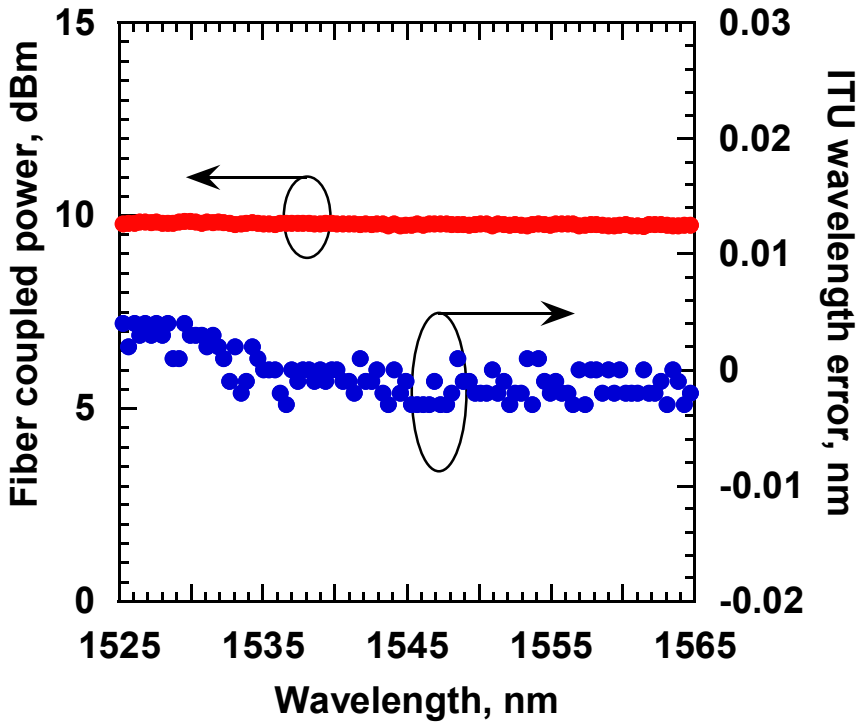
CW close loop performance



- Fiber coupled power = 10 dBm +/- 0.05 dB
- Wavelength deviation <+/- 3.5 pm

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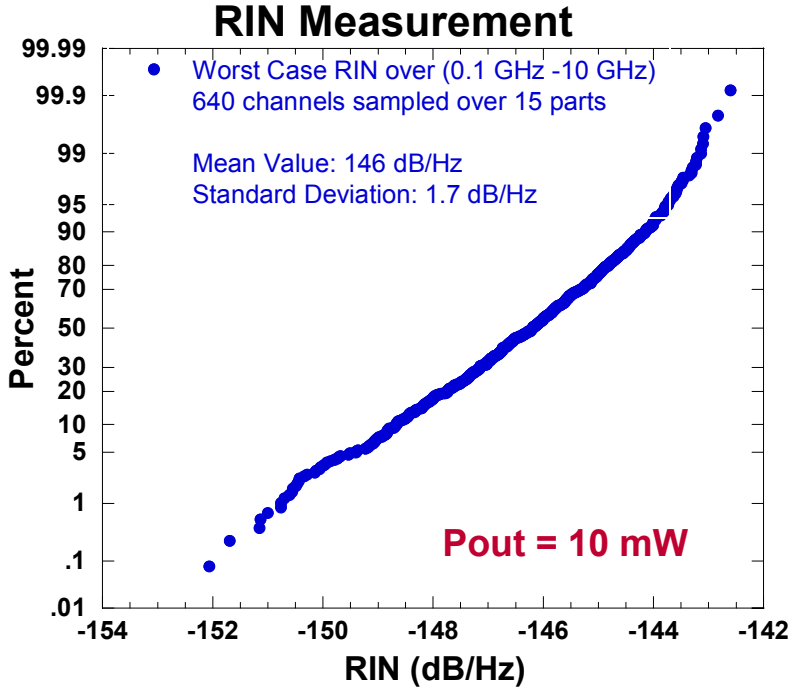
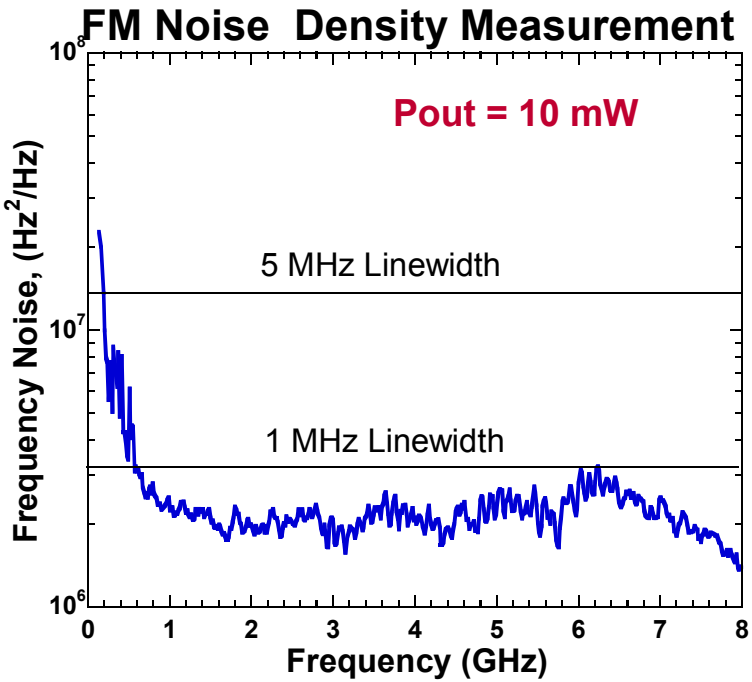
RIN and Linewidth of SOA Amplified SG-DBR





- SOA does not degrade RIN & Linewidth
- RIN ~ -146 dB/Hz
- Linewidth measured by self-homodyne technique at subsystem level <10 MHz
- Linewidth ~ 1 MHz using FM Noise Density measurement (more accurate than self-homodyne method).

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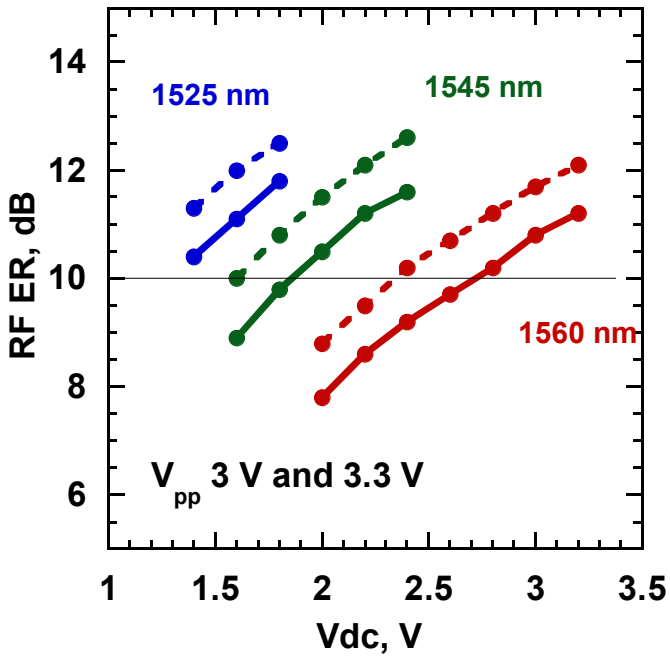
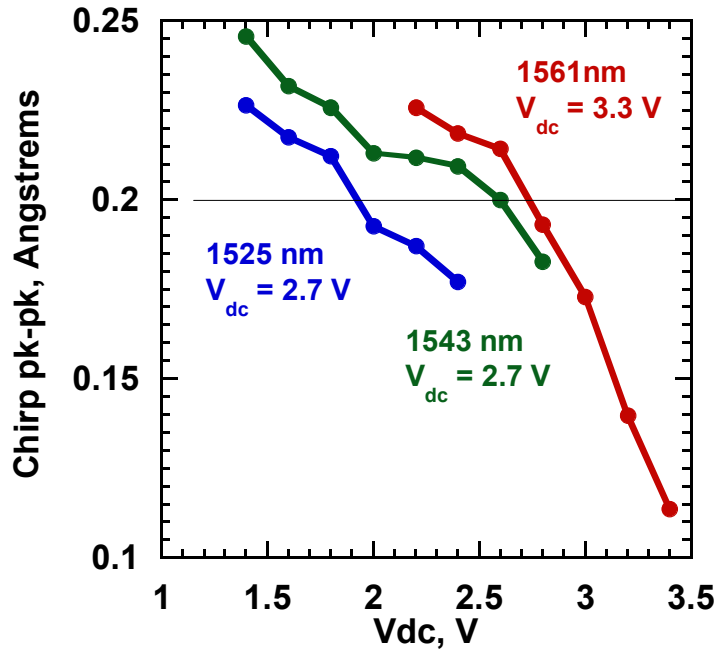
High-speed performance: *RF* ER & Chirp





- Chirp mapped out using Time Resolved Spectroscopy
- Curved waveguide and multilayer AR coating eliminate optical cross-talk
- Low on-chip electrical cross-talk
- EA modulator chirp can be adjusted by V_{dc} and V_{p-p}
- *RF ER* > 10 dB, chirp < 0.2 A over wide tuning range

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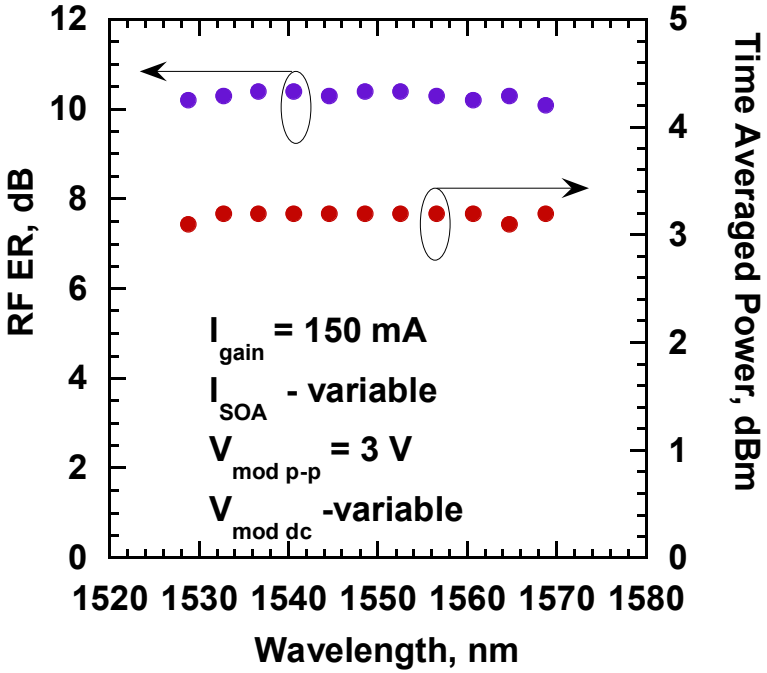
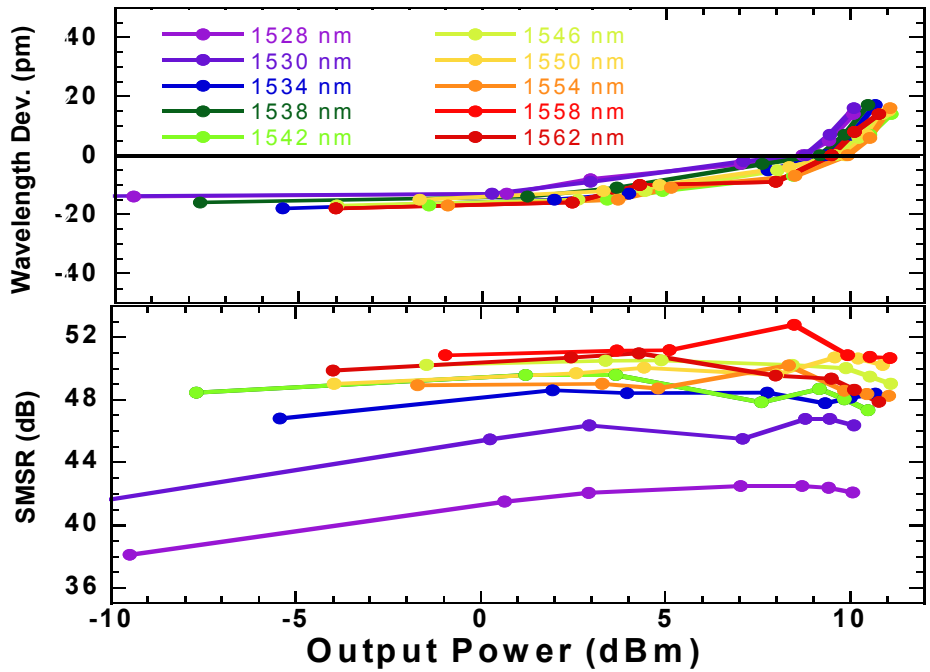
Modulated Performance: *RF ER* & P_{ave} & VOA Operation





- Time-averaged power 3 dBm and RF ER > 10 dB across C-band
- Output power dynamic range of ~20 dB w/ small change in SMSR and Wavelength (open loop operation)

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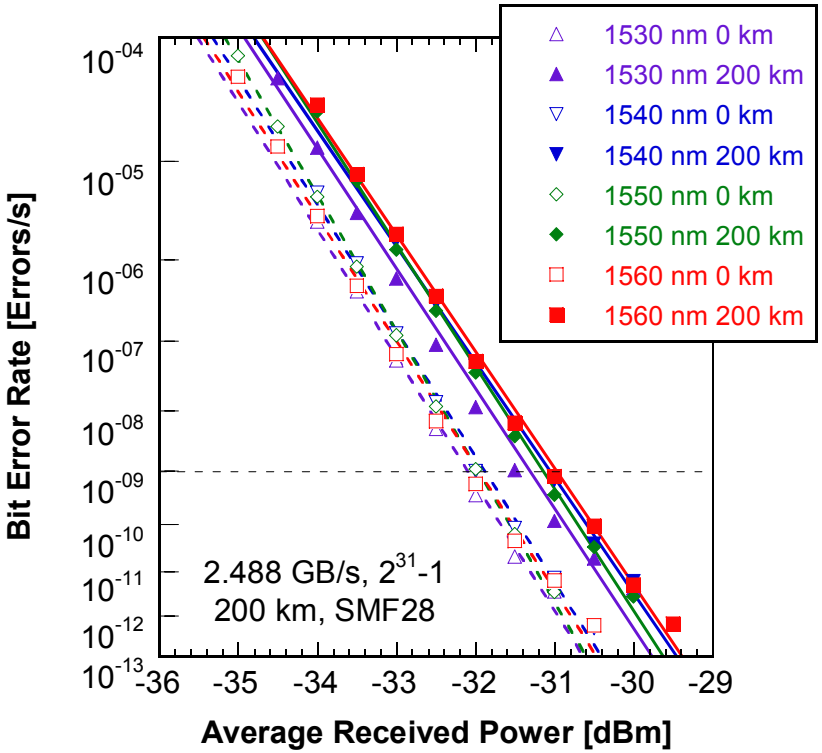
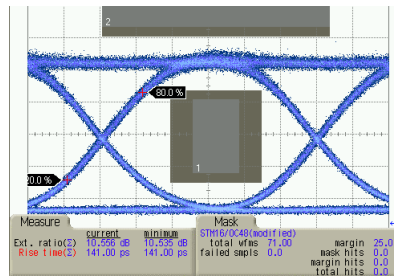
Transmission characteristics

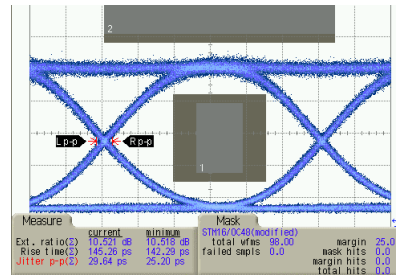


- < ~ 1 dB DP over 200 km NDSF
- Supports OC-48 with FEC

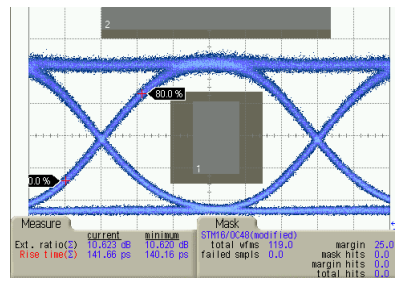
1528 nm



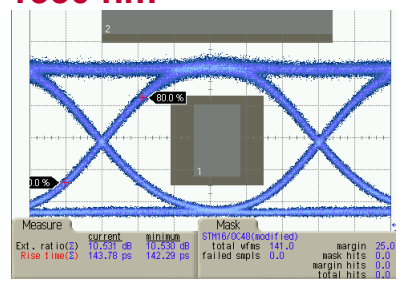
1560 nm



1540 nm



1550 nm

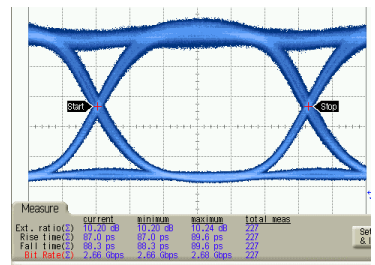


PRBS 2^{31}-1 at 2.5 Gb/s

4^{th} order Bessel-Thomson filter

SONET mask with 25% margin

Unfiltered 2.7 Gb/s



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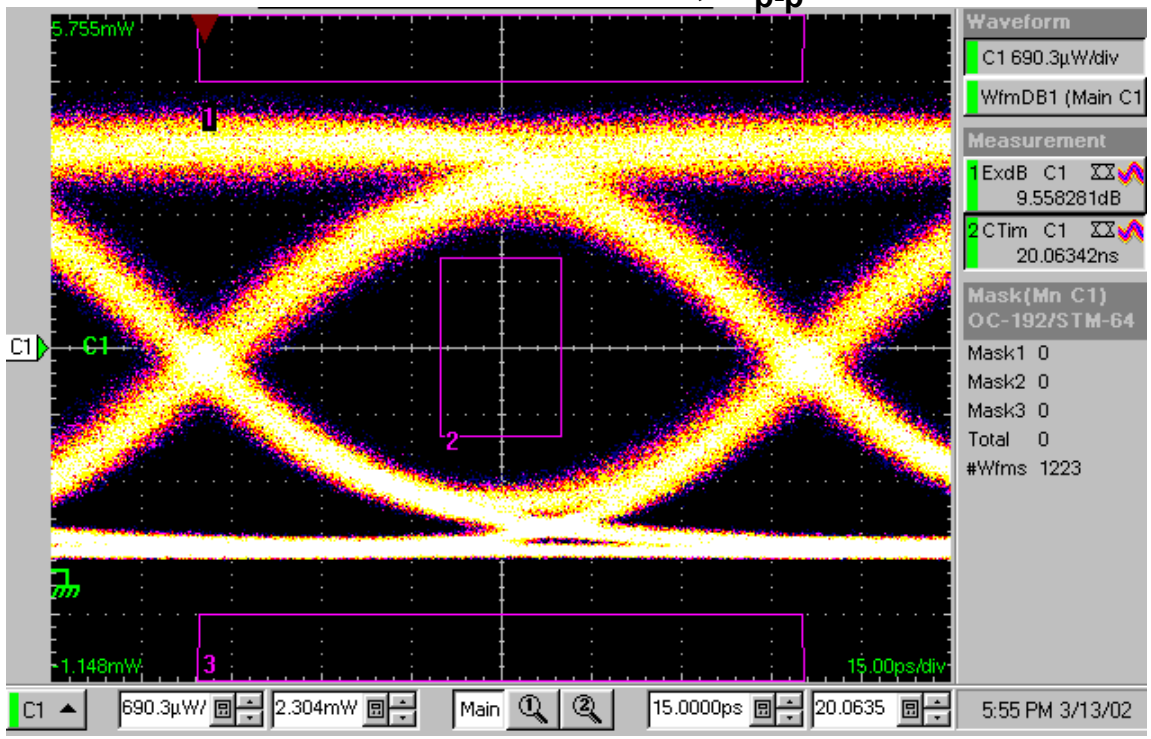
OC-192 Operation of EAM

PRBS 2^{31}-1, V_{p-p} = 3V



- Integration technology compatible with higher bit rates
- > 10 dB *RF ER* across C-band

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Summary

- **SG-DBR lasers meet the requirements of many market segments: from Metro to Ultra-Long Haul.**
- **Monolithic SGDBR-SOA-EAM chip using platform technology**
  - High yield
  - Low cost
  - High Volume
- **SGDBR-SOA-EAM characteristics:**
  - Wide Tuning (>40 nm)
  - High Power (>10 mW CW)
  - 3 dBm time averaged power and >10 dB *RF ER* across C-band
  - Support OC-48 with FEC
- **Fully functional widely-tunable Transmitter with integrated wavelength locker and close loops control (power, wavelength, mode, temperature)**
- **SGDBR-SOA-EAM integration technology is compatible with higher output power and bit rates**