Low-Speed Lasers, Nonlinearities, and EDC

Norman Swenson, ClariPhy
Paul Voois, ClariPhy
Dubravko Babic, Etanvie Technologies

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Background

- EDC offers opportunity to reduce cost of module in addition to extending link length
  - EDC can compensate for distortion caused by:
    - lower bandwidth fiber
    - reduced bandwidth of low-speed electro-optical components
- Nonlinearities complicate the issue
  - EDC usually assumes linear channel impairments
  - Nonlinearities have implications for multi-level modulation (PAM-4)

Motivating Questions

- Does nonlinearity of low-speed (e.g. 2Gbps or 4Gbps) laser preclude use in EDC-enabled 10Gbps link?
- Does nonlinearity of low-speed laser preclude use with PAM modulation?

Types of Nonlinearity Addressed

- Data-dependent nonlinearity
  - Caused by nonlinear laser rate equations, e.g., relaxation oscillations
  - Also caused by a low bandwidth filter (e.g., package parasitics) preceding a memoryless nonlinearity
- Nonlinearity of L-I curve
  - Pseudo-static nonlinearity
  - “Steady-state” variation of optical power with modulation current level

Data-Dependent Nonlinearity

- The central issue is: Can the optical output be expressed as a linear superposition of pulses?
- That is, can the optical output be expressed as:

$$P(t) = b + \sum_{i=-a}^{m} d_i p(t - iT)$$

where b is the bias, $p(t)$ is the basic pulse shape, a and m are the anticipation and memory in symbol periods, respectively, and d_i is the data symbol

$d_i \in \{0,1\}$ for NRZ

$d_i \in \{0,1,2,3\}$ for PAM - 4

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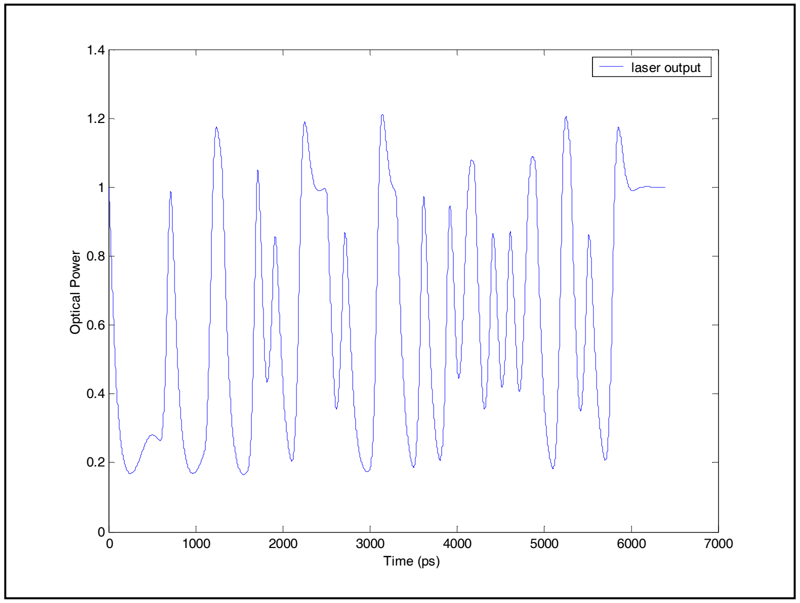
Approach

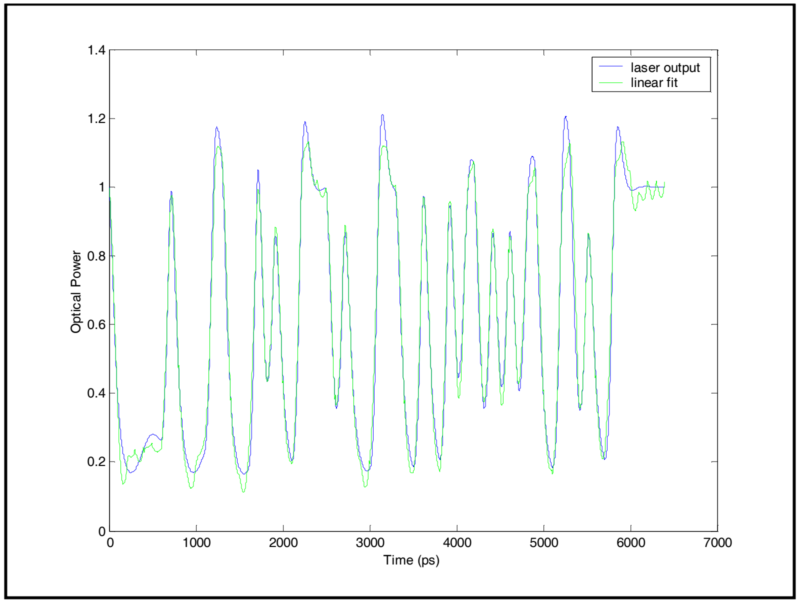
- Drive low-speed laser by high-speed signal
  - Simulate via laser-rate equations
  - Experimentally
- Digitize received waveform
- Find best fit for b and $p(t)$ given data sequence and reasonable values for a and m
- Compare linear approximation of received signal to actual received signal
- Calculate a signal to distortion ratio (ratio of variance of signal to variance of error signal)

Simulation Results



Laser cutoff frequency: 4 GHz; 64-bit PRBS

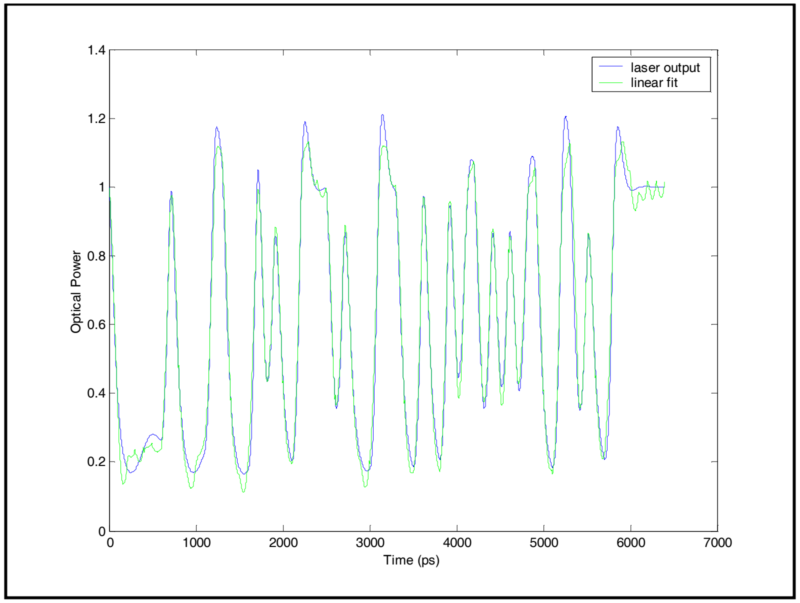
Simulation Results



Laser cutoff frequency: 4 GHz; 64-bit PRBS

- Laser output is reasonably linear, but nonlinearities are evident
  – SDR is 17.5 dB

Simulation Results



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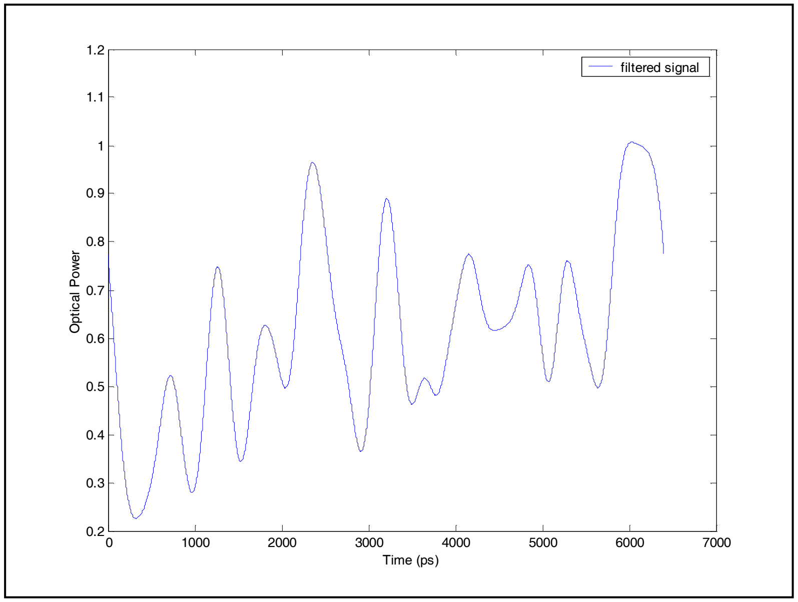
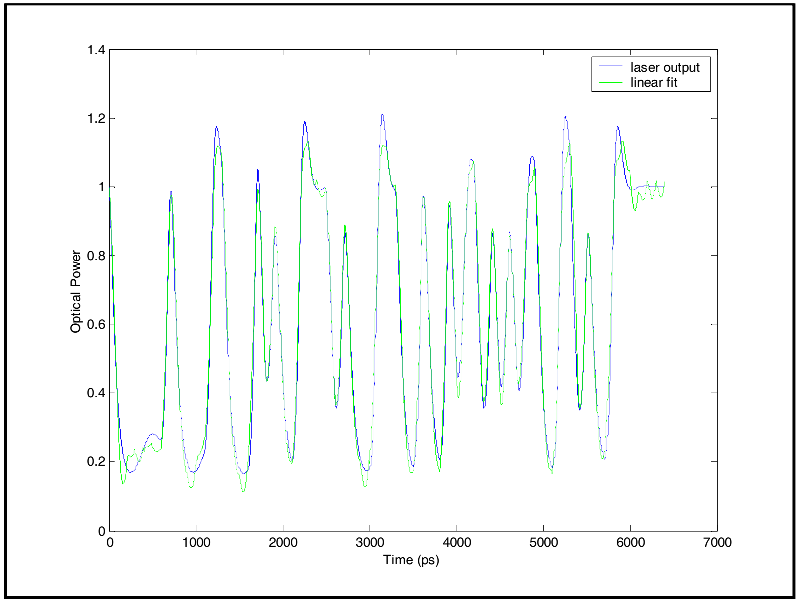


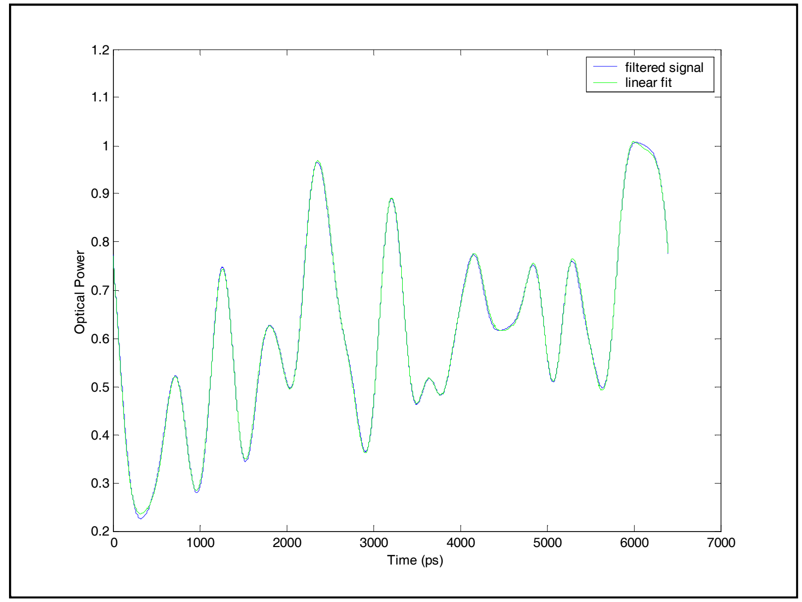
Lowpass filter: Gaussian, 3dB BW = 500/.3 = 1.67GHz

- Laser output is reasonably linear, but nonlinearities are evident
  - SDR is 17.5 dB

Simulation Results



Laser cutoff frequency: 4 GHz; 64-bit PRBS



Lowpass filter: Gaussian, 3dB BW = 500/.3 = 1.67GHz

- Laser output is reasonably linear, but nonlinearities are evident
  - SDR is 17.5 dB
- Filtering (by fiber or low-speed receiver) removes nonlinear components
  - SDR is 32 dB

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Lab Experiment

- Modulated 1310 nm DFB and FP OC-48 lasers
  - 3.2 Gbps NRZ
  - Different extinction ratios
  - Optical output power -2.3 dBm
- Digitized optical power waveform using sampling oscilloscope
- Filtered via simulation using 3-pole Butterworth filter, 6dB electrical BW = 2 GHz
- Computed SDR for filtered and unfiltered waveforms

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Experimental Results

	Unfiltered SDR	Filtered SDR
FP, ER = 6dB	23.9 dB	32.7 dB
DFB, ER = 6 dB	27.0 dB	29.0 dB
FP, ER = 9 dB	16.4 dB	29.7 dB
DFB, ER = 9 dB	22.4 dB	28.6 dB

Preliminary Conclusions

- Transient nonlinearities of the low-speed lasers tested are largely outside the channel bandwidth on the channels of interest
- Transient nonlinearities should not preclude the use of low-speed lasers when combined with EDC
  - However, the EDC must be powerful enough to compensate for the combined bandlimiting of the laser and fiber
- Further work is required to finalize these conclusions:
  - Experimental validation with 10 Gbps modulation
  - PAM-4 modulation
  - Other laser types (long wavelength VCSELs)

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Experimental Results on the Linearity of Dynamic LI Curves

Motivation

- PAM-4 modulation assumes equally spaced transmit levels
- The simplest way to generate these equally-spaced levels is to use a laser with a linear *dynamic LI curve*
- This work experimentally investigates dynamic LI curves

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Definitions

- What is an LI curve?
  - L = light (OMA) out of laser
  - I = current into laser
- *Dynamic* LI curve
  - Generated by varying a modulated input current at a fixed average optical power
  - Constant average optical power ➔ constant temperature
- *Static* LI curve
  - Typically this is what is shown on data sheets
  - Generated by (slowly) sweeping a DC input current
  - Nonlinear: self-heating of laser causes rolloff
  - Doesn't reflect the laser operation under modulated conditions
- Dynamic LI curve is "Pseudo-static"
  - Dwell at one level long enough for data transition transients to die out
  - Change levels rapidly enough to avoid thermal effects from self-heating
  - Accurately reflects LI performance under modulated conditions

Experiment Description

- DUTs
  - Opnext TRF591x OC-48 SFP module
    - 1310 nm FP laser, 2km reach
  - Opnext TRF592x OC-48 SFP module
    - 1310 nm DFB laser, 15 km reach
- Data rate: 2.5 Gbit/s
- Measurement procedure
  - Fix module's average optical output power P_{avg}
  - Vary module current I over several measured values
  - Measure output OMA on oscilloscope for each measured current value

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Description (Cont.)

- Module current
  - Measured value I is total current into module
  - Individual values of laser bias current (I_b) and modulation current (I_{mod}) are unknown
- Modulation current determined by the <u>difference</u> between module current measurements.
  - For a fixed P_{avg} and module current measurements $I(1)$, $I(2)$:
    - $I_{mod}(2) - I_{mod}(1) = k\,[I(2) - I(1)]$, where k is a constant
    - Opnext: $k \sim 60\%$
  - Remainder of the change in module current goes to a bypass circuit

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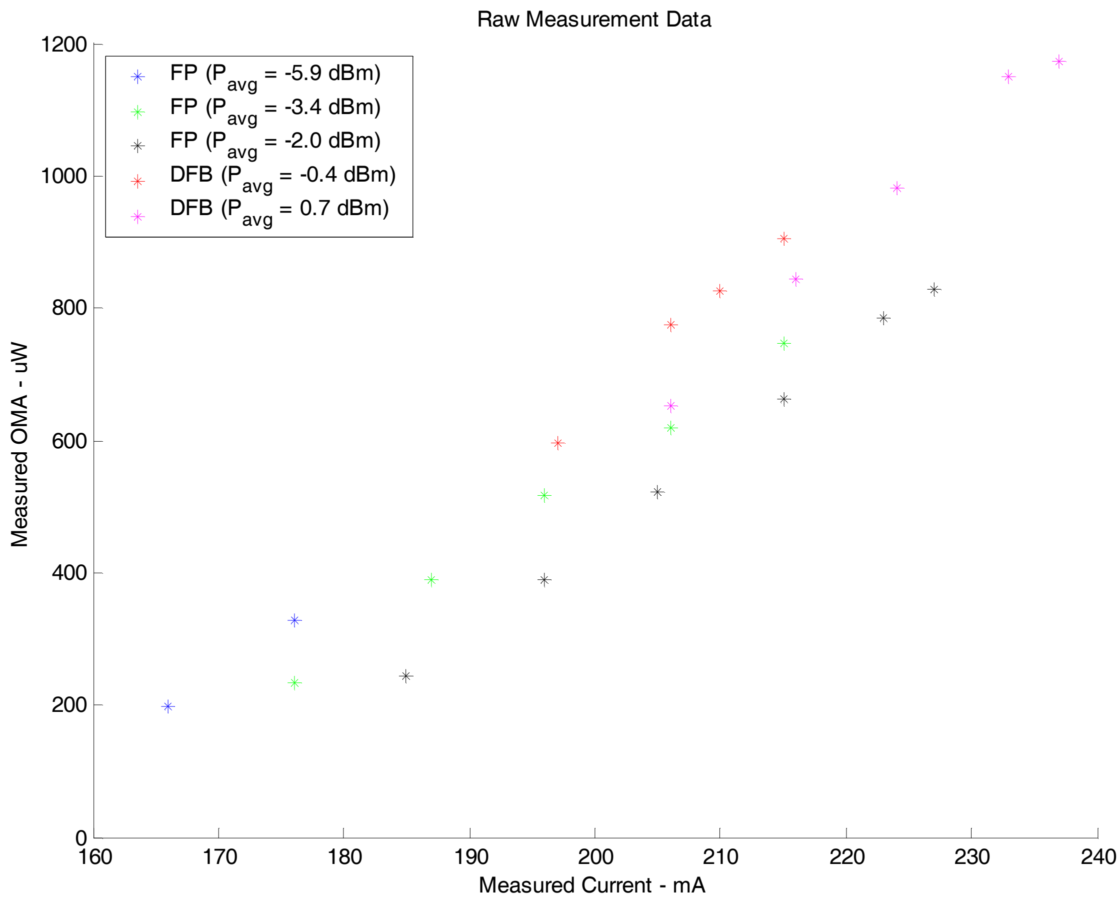
Raw Measured Data



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Construction of Dynamic LI Curves

- Each curve to follow shows output optical power (not OMA) vs. modulation current
- Each curve corresponds to a fixed P_{avg}
- Each figure includes best linear fit overlay
- Assumptions
  - Modulation current is symmetric about average power operating point
  - Innermost two points on each curve determined by linear interpolation
  - $k = 1$ (affects slope, not linearity)

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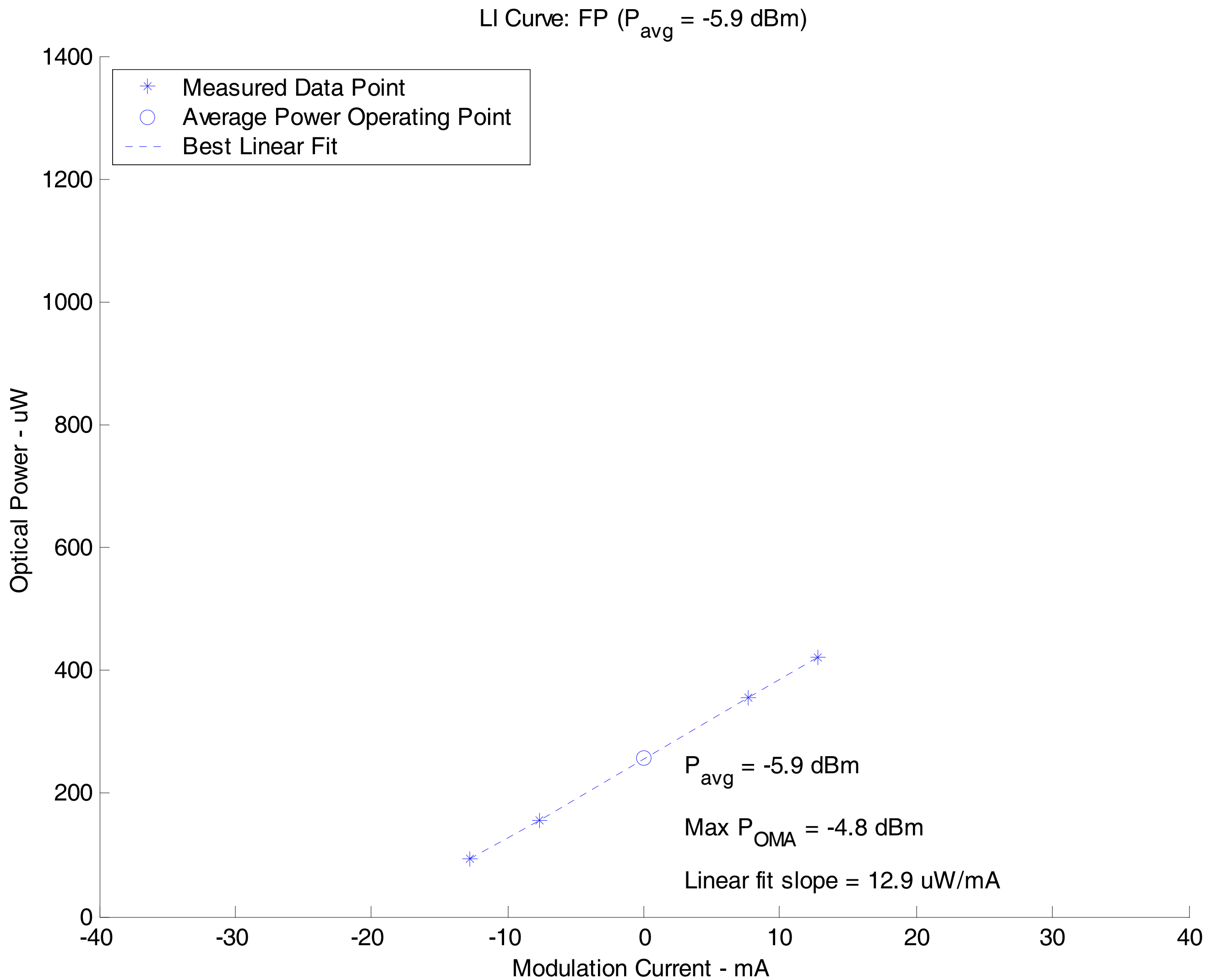
Results

- Both devices (FP, DFB) show good linearity over a wide operating range
  - FP: P_{OMA} up to -0.8 dBm
  - DFB: P_{OMA} up to 0.7 dBm
  - Slopes are consistent for various P_{avg}
- Suggests suitability for PAM-4
- Further work:
  - Higher data rates
  - Wider range of lasers



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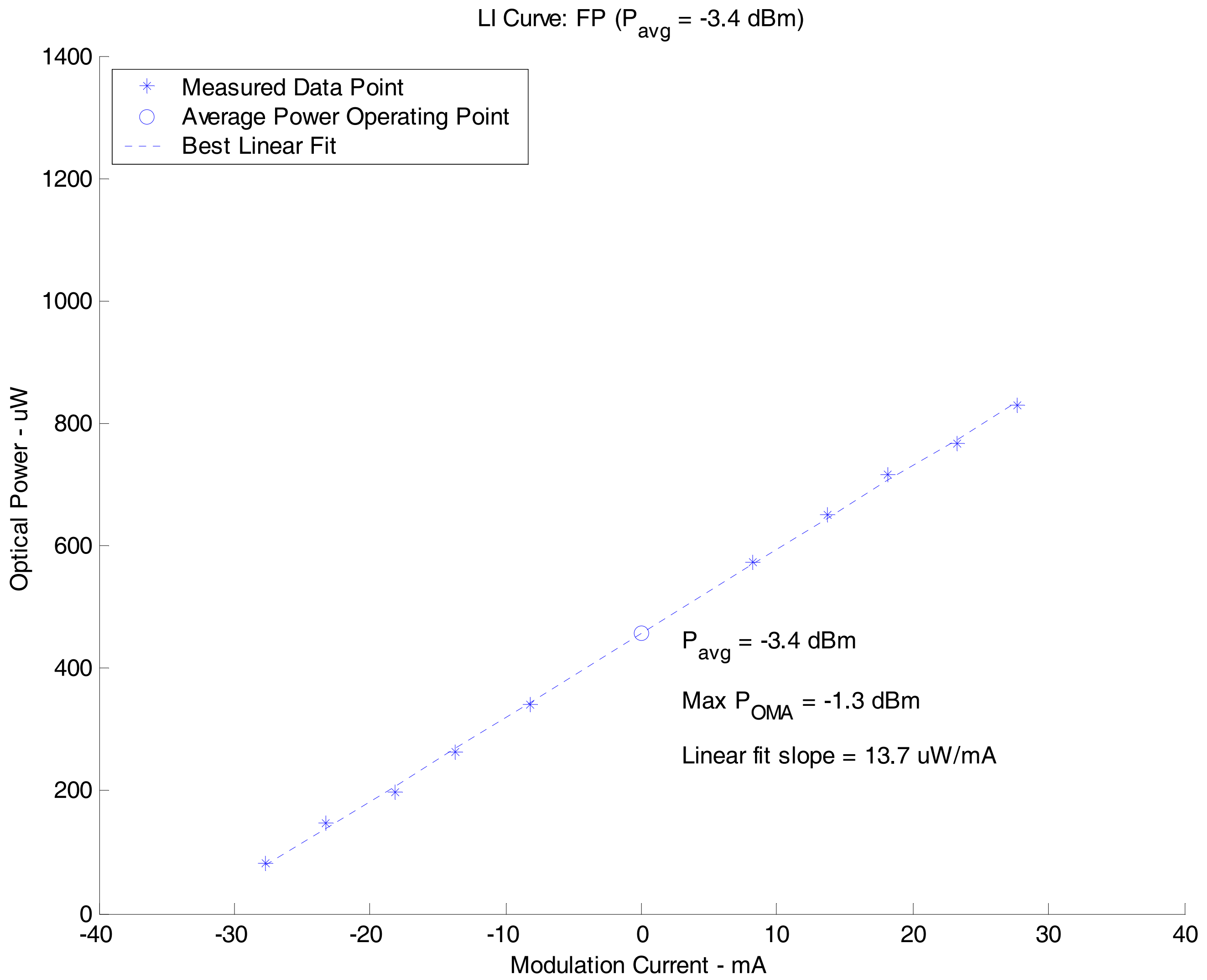

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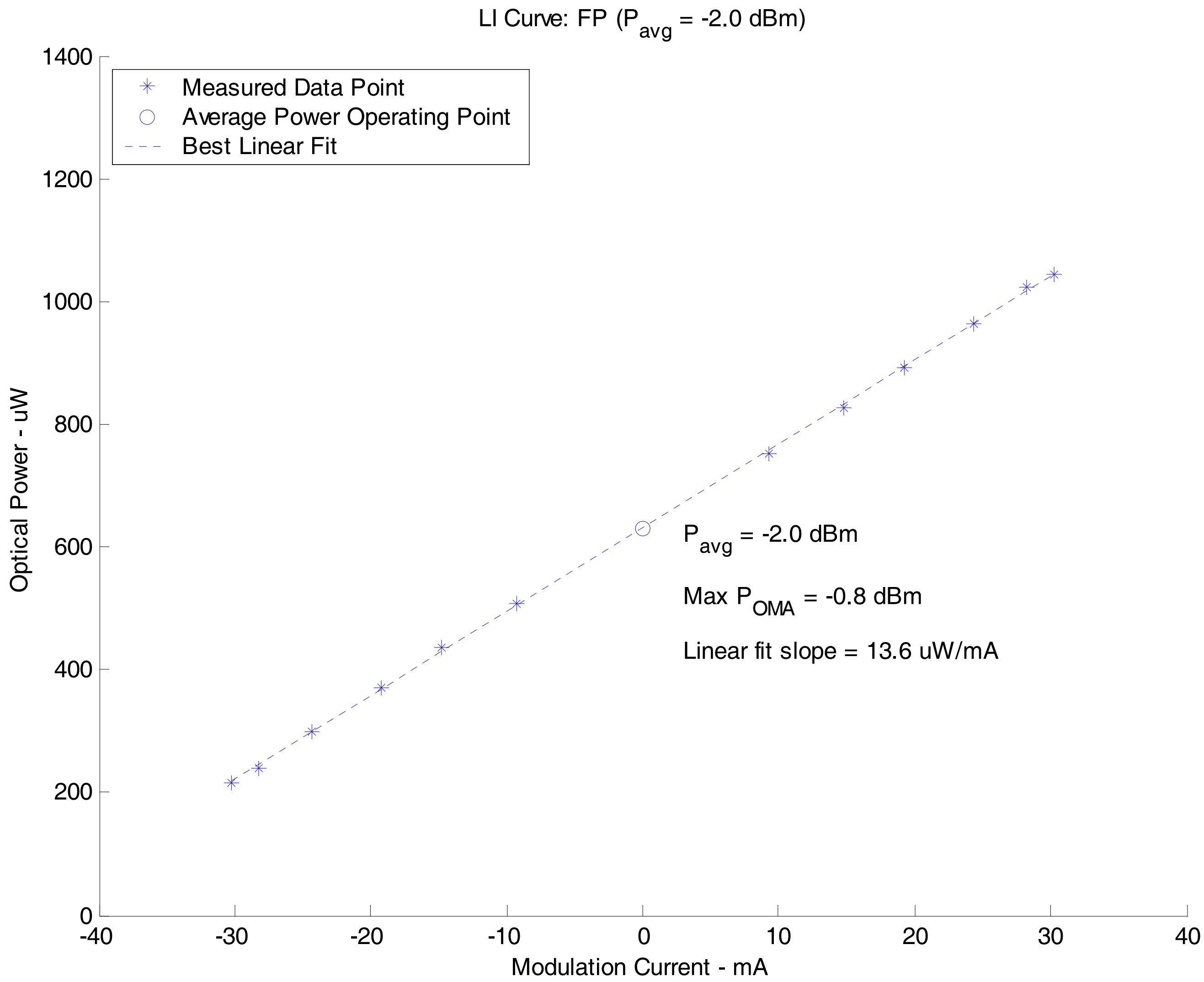
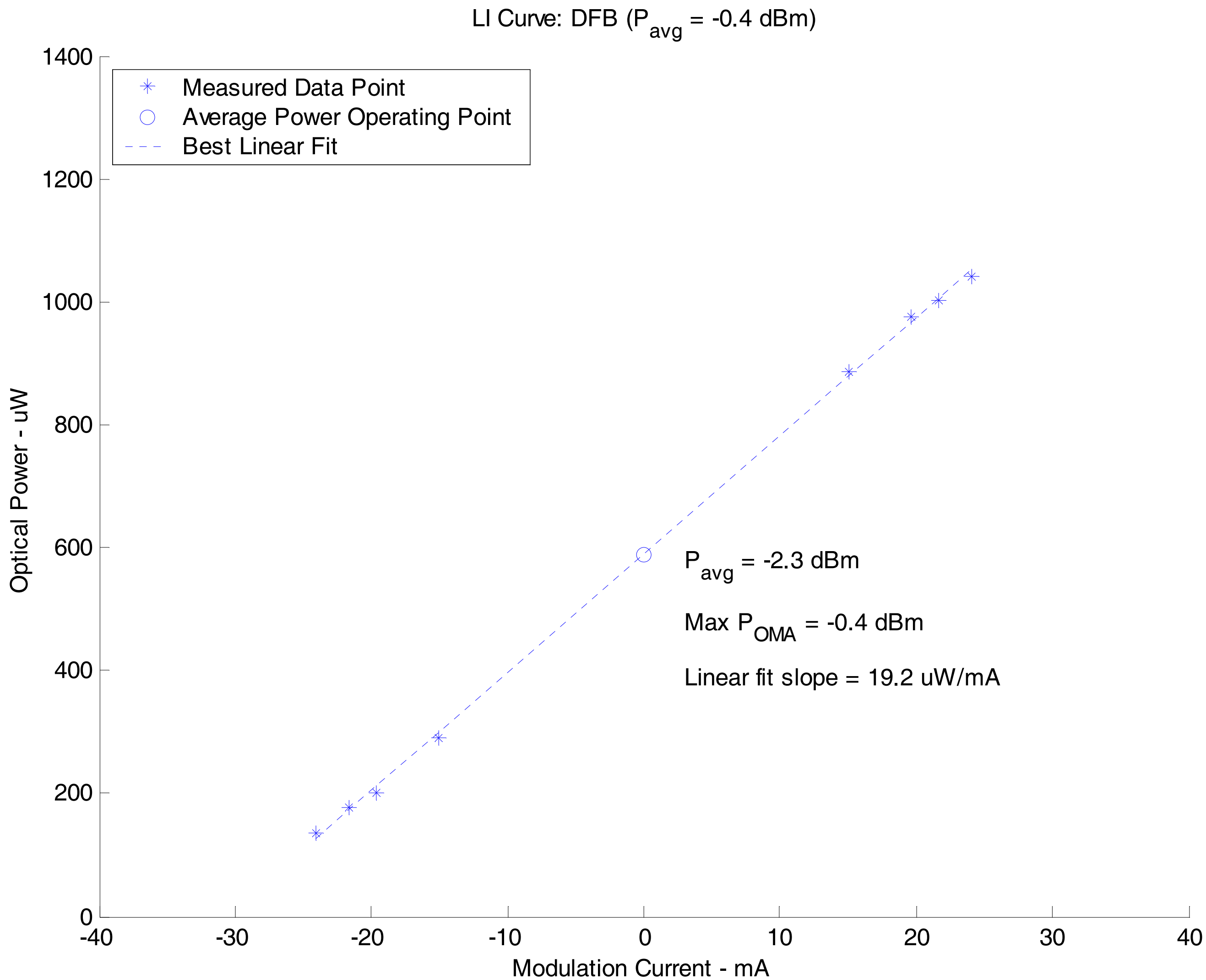


LI Curve: FP (Pavg = -2.0 dBm)
Measured Data Point
Average Power Operating Point
Best Linear Fit
Pavg = -2.0 dBm
Max POMA = -0.8 dBm
Linear fit slope = 13.6 uW/mA
Optical Power - uW
Modulation Current - mA
0
200
400
600
800
1000
1200
1400
-40
-30
-20
-10
0
10
20
30
40



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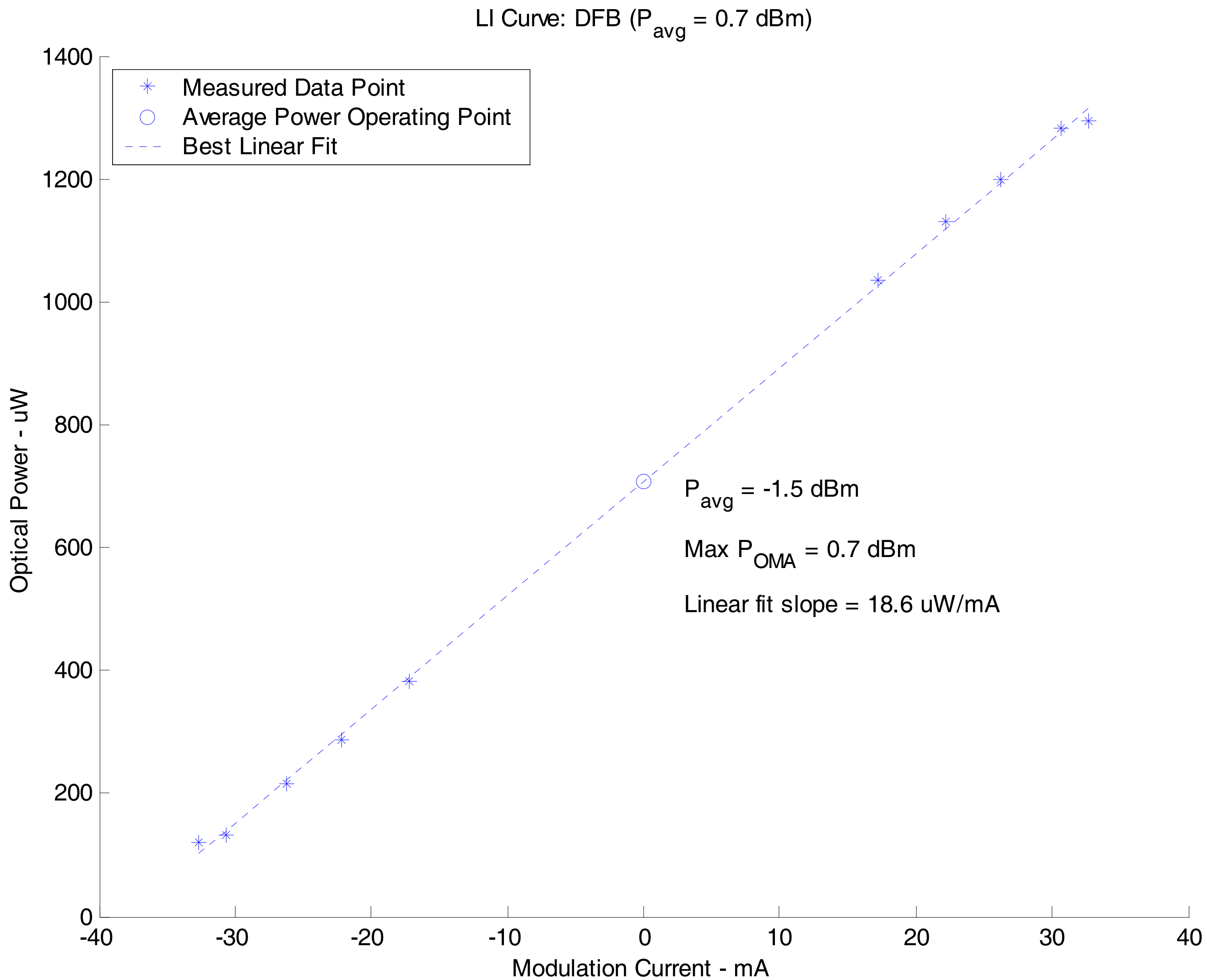

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