Recent Developments in Transceiver SoC Design for Next Generation Optical Networks

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Motivation

BoF circuit and system design

Measured results

Summary and future work
Motivation

• Mobile data to grow >1000x over 2010 to 2020 [1]
• Expected 5G initial deployment in 2020 [1]

• New emerged mm-wave spectrum for 5G [2]
  • 26GHz, 28GHz, 32GHz, 38GHz, 70/80GHz…

Motivation

- Macro/pico cells widely used to extend coverage and data throughput capacity in 4G LTE and 5G cellular network
- Wired connection sometimes physically impractical or costly
- **Hybrid fiber-wireless network**: flexible and high performance solution for short-range backhaul links deployment
Motivation

Conventional Solution:

Proposed Solution:

- Conventional fiber-wireless network composed of discrete O/E and RF components is costly and power hungry
- Redundant baseband digital processing introduces large overhead and latency
Previous Work

- 60GHz 4Gb/s NRZ to QPSK Modulator [1]

- Work at 60GHz
- No power amplifier integrated -> **external PA needed**
- No IQ calibration -> **may suffer from image tone**
- No on-chip demodulation -> **difficult to measure BER**

[Y. Wang, ESSCIRC 2015]
Previous Work

- 60GHz 4Gb/s NRZ to QPSK Modulator [1]
  - Data rate limited to 4Gb/s
  - Unbalance I/Q performance -> May be IQ mismatch

EVM = $-14\text{dB}$

EVM = $-12\text{dB}$

[Y. Wang, ESSCIRC 2015]
Outline

- Motivation
- BoF circuit and system design
  - Optical RX with integrated PD
  - Wideband QPSK TX
  - Built-in-self-test
- Measured results
- Summary and future work
The BoF System Architecture
Optical Receiver

- Optical RX
  - on-chip PD
  - inv-based TIA
  - 3-Stage CTLE
  - MA/LA

[Q. Pan, VLSI 2014]
P-well/Deep N-well PD Structure

- Eliminate the slow substrate diffusion current
- Deeper junction depth and lighter doping concentration
- Compatible with optical receiver design when operating in the avalanche mode
- **Measured Responsivity**

  - Input light power (-5dBm) is chosen according to sensitivity to work in the linear region
  - 51mA/W @0.5V; 272mA/W @12.3V (optimal); 1.03A/W @ 12.8V (maximum)
P-well/Deep N-well PD Structure

- Measured Optical Frequency Response

- Normalized to DC responsivity @ avalanche mode
- Slow roll-off frequency response
- Fitting -3dB bandwidth: 500MHz
Inductive Cascode Inverter-Based TIA

- Given a 480-fF PD capacitance, boost the bandwidth and minimize the input referred noise (IRN)
By interpolating the poles and zeros, a slow roll-up (5~10dB/decade) response can be achieved.
Slow Roll-Up 3-Stage Cascaded CTLE

- Measured Electrical Frequency Response
  - The gain of optical RX

- Tested by direct probing without the on-chip PD
- 33-dB CTLE tuning range
QPSK Transmitter

- QPSK TX
  - 2-stage PPF
  - Wideband PA
  - Gilbert mixer
  - Ripple cancel
Wideband Power Amplifier

- Two amplification stages with neutralization cap
- Coupled resonator wideband matching network

<table>
<thead>
<tr>
<th>M1A/M1B</th>
<th>CC1</th>
<th>M2A/M2B</th>
<th>CC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>64,\mu m/60,nm</td>
<td>23fF</td>
<td>128,\mu m/60,nm</td>
<td>45fF</td>
</tr>
</tbody>
</table>
Coupled Resonator based Wideband Matching

- Transform the loading to $Z_{opt}$ obtained from load pull simulation
- $R_L = 50\Omega$, $C_L = 25\, fF$ (PAD capacitance)
- $Z_{opt}^* : 37.5\, \Omega \parallel 123\, fF$

How to achieve wideband impedance transformation with low insertion loss?
Coupled Resonator based Wideband Matching

- The effect of $k$ and $Q$

  - **large** $k$ pushes two poles away
  - central freq increases with $k$
  - When is the flattest response?

  - **large** $Q$ leads to large ripple
  - $Q$ has little influence on peak magnitude
Coupled Resonator based Wideband Matching

- Minimal gain ripple condition: $k^2(Q^2 + 1) = 1$
- More accurate than previous mentioned $k^2Q^2 = 1$ [1]

[C. Li, TMTT 2012]
Coupled Resonator based Wideband Matching

- The impedance transformation achieved when \( \frac{L_2}{L_1} = \frac{R_L}{R_s} \)

Simulated impedance

Simulated efficiency

[H. Jia, A-SSCC 2016]
Wideband Power Amplifier

- PA Input/Inter-Stage Matching Network
  - Take advantage of gain ripple & bandwidth trade-off
  - Use the IF low pass feature to compensate ripple

- Simulated gain ripple reduces from 3.8dB to 1.3dB
BIST

- 2-stage PPF
- Cap coupling
- Current bleeding mixer
- CML driver
Built-In-Self-Test

- On Chip Demodulator to support BER test

- On-chip demod.
- Cap coupled
- Sharing the same LO with QPSK Tx

Power off when not in use
Cap. Couple Instead of Ind. Couple

- Capacitive coupling (sensing voltage)
- Inductive coupling (sensing current)

Simulated gain response from PA output stage to BIST input

- Cap coupling maintains the TX’s wideband property
Outline

- Motivation
- BoF circuit and system design
- Measured results
- Summary and future work
Chip Photo and Power Consumption

- Optical RX
- QPSK TX
- BIST
- Bandgap

**Chip Dimensions:**
- Width: 2.5mm
- Height: 0.9mm

**Power Consumption:**
- QPSK TX: 0.59mm²
- BIST: 0.19mm²
- Optical RX: 0.26mm²
- Others: 15.8mW, 6%
- Optical Rx: 103mW, 38%
- QPSK Tx (w. LO buffer): 122mW, 44%
- BIST: 33mW, 12%

**Technology:**
- 65nm CMOS process
Continuous Wave Measured Results

The QPSK TX Conversion Gain

- 24.7dB at 32GHz, >24dB from 25.3 to 40.3GHz
- 3.4dB gain ripple (no include IF path LPF)
- 13.8dBm Psat at 30GHz
The QPSK TX Large Signal Performance

- Measured 10.1dBm output 1dB point
- Measured 17.7dBm output IP3 point
Continuous Wave Measured Results

- The QPSK TX Image Rejection Ratio (IRR)
  - Improved by manually tuning the PPF res array

- IRR improved from -19.8dBc to -38.8dBc
- -38.8dBc image rejection and -46.3dBc LO rejection
Optical RX Measured Results

- Measurement Setup
  - External phase shifter

- Manually tuning the phase for optimal sampling
- The error free sampling phase range is measured
Optical RX Measured Results

- The eye and BER from RX’s output

- 0.38UI error free sampling CLK phase range
Optical RX Measured Results

- Optical RX sensitivity

- The minimal error free input amplitude is 21.5mVp-p
- Converts to 165uAmp-p using a 80Ω input impedance
BoF Data Measured Results

Measurement Setup

- **PC**
- **ARM**
- **Power supply**

PatternPro SDG 12070, ~30Gb/s

Optical RX

Demux

QPSK TX

BIST

BIST OUT₁

BIST OUT₂

Sub-sampling oscilloscope

Real-time Oscilloscope

R&S FSW67, ~67GHz

R&S RTO1044

~4GHz, 20GS/s

Error checker

PatternPro SDA 13020, ~32Gb/s

Spectrum analyzer

Keysight E8257D, ~67GHz

32G LO

50Ω

Keysight DCA-X 86100D, ~50GHz
BoF Data Measured Results

Measurement Setup

- On-chip probing for high speed signals
- BERT system, signal gen, subsampling osc, real time osc
BoF Data Measured Results

- **The EVM of TX’s output**

  - 6.4Gb/s QPSK
    - EVM = -18.8dB (32767 symbols)

  - 12.8Gb/s QPSK
    - EVM = -15.6dB (32767 symbols)

- Using $2^{15}-1$ PRBS pattern, 32767 symbols collected
- Degraded due to insufficient OSC’s BW
The eye and BER from BIST’s output

- 0.49UI error free range at 16.0Gb/s data rate
## Performance Summary and Comparison

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<thead>
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<tbody>
<tr>
<td><strong>Process</strong></td>
<td>65nm CMOS</td>
<td>65nm CMOS</td>
<td>65nm CMOS</td>
<td>40nm LP CMOS</td>
</tr>
<tr>
<td><strong>Freq. (GHz)</strong></td>
<td>32</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td><strong>DR (Gb/s)</strong></td>
<td>16.0 (QPSK)</td>
<td>7 (16QAM)</td>
<td>14.08/28.16 (QPSK/16QAM)</td>
<td>3.5/7 (QPSK/16QAM)</td>
</tr>
<tr>
<td><strong>TX EVM (dB)</strong></td>
<td>-15.6* (TX-to-BIST)</td>
<td>-21 (TX-to-BIST)</td>
<td>-20.1/-20.0 (TX-to-RX)</td>
<td>-14.8/-15.2 (TX-to-RX)</td>
</tr>
<tr>
<td><strong>TX P&lt;sub&gt;DC&lt;/sub&gt; (mW)</strong></td>
<td>138 Excl. LO</td>
<td>174</td>
<td>186</td>
<td>181***</td>
</tr>
<tr>
<td><strong>TX Eff. (pJ/b)</strong></td>
<td>8.6</td>
<td>24.9</td>
<td>13.2/6.6</td>
<td>78.4/39.2</td>
</tr>
<tr>
<td><strong>CG (dB)</strong></td>
<td>24.7</td>
<td>N/A</td>
<td>15</td>
<td>31</td>
</tr>
<tr>
<td><strong>P&lt;sub&gt;-1db&lt;/sub&gt; (dBm)</strong></td>
<td>10.1</td>
<td>6.3</td>
<td>10.3**</td>
<td>10.8***</td>
</tr>
<tr>
<td><strong>BIST</strong></td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>BER</strong></td>
<td>&lt;10&lt;sup&gt;-12&lt;/sup&gt; (TX-to-BIST)</td>
<td>N/A</td>
<td>N/A</td>
<td>&lt;10&lt;sup&gt;-4&lt;/sup&gt; (TX-to-RX at 3.6m)</td>
</tr>
<tr>
<td><strong>TX frac. BW (%)</strong></td>
<td>46</td>
<td>N/A</td>
<td>N/A</td>
<td>10</td>
</tr>
<tr>
<td><strong>TX Area (mm&lt;sup&gt;2&lt;/sup&gt;)</strong></td>
<td>0.59</td>
<td>0.79</td>
<td>1.03</td>
<td>1.5*</td>
</tr>
</tbody>
</table>

*EVM at 12.8Gb/s  **Saturated output power  ***Each TX path
Summary

- Wideband 32GHz QPSK with integrated optical RX and BIST is presented

- Coupled resonator based wideband matching
  - Ripple cancellation using IF intrinsic LPF

- An error-free 16.0Gb/s data rate is achieved at 8.6pJ/b bit efficiency