Optical Modulators for Transparent Analog Fiber Link


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* Now with CREOL, Univ. of Central Florida
** With Photonic Systems Inc. Boston, Mass. USA
*** Now with Sun MicroSystems, San Diego
Outline of Presentation

• Introduction: Analog fiber link
• Electroabsorption Modulator
• Multiple Quantum Wells and Gain Saturation
• Large SFDR modulation
• E-O effect in InP nanowires
• Conclusion
Analog Fiber-Optic Link

Direct Modulation

External Modulation

RF Input

RF Output

Transmitter

Receiver

Optical Fiber

Laser

Optical Modulator

RF Input

Optical Output

Transmitter

Optical Output
Analog Fiber-Optic Link Applications

- CATV
- Antenna Remoting
- Phased Array Antenna
Externally Modulated Analog Fiber Optics Link

- Avoids the relaxation oscillation and reduces the chirp of the direct modulated laser diode; good for wide bandwidth modulation.

- Link RF gain, $G \sim (P_{opt})^2$
Important Analog Link Parameters

1. RF Gain: Output RF power/Input RF power
2. Bandwidth: 3 dB RF gain cut-off frequency bandwidth
3. Noise Figure: Input SNR/Output SNR
4. Spurious Free (or Intermodulation free) Dynamic Range:
   RF power range above noise and intermod distortions
RF Gain of the External Intensity Modulated link

Transmitter

\[ P_{\text{opt}} t_{ff} \left[ T(V_b) + T'(V_b) \right] \nu_{ac} \cos \omega t \]

\[ V_b + \nu_{ac} \cos \omega t \]

Detector

\[ R_d P_{\text{opt}} L \left[ T(V_b) + T'(V_b) \right] \nu_{ac} \cos \omega t \]

\[ G = \frac{P_{RF-out}}{P_{RF-in}} \propto P_{\text{opt}}^2 \left[ T'(V_b)^2 \right] \left[ L_f \right] \left[ R_d^2 \right] \]

Modulator

\[ G = P_{\text{opt}}^2 \left[ \frac{\pi^2 t_{ff}^2 R_{in}}{V^2} \right] \left[ L_f^2 \right] \left[ R_d^2 R_{out} \right] \]

Detector

where equivalent \( V_{\pi} \)

\[ V_{\pi} = \pi/(2 \frac{dT}{dV}), \]
RF Gain as a function of $V_\pi$ at different optical powers

$\eta_{\text{ins}} = 0.1$;
$\eta_d = 1 \text{ A/W}$
$L_f = 1$
External Modulator Candidates

**Electro-optic Modulator:**
(a) Lithium Niobate  
(b) Semiconductor  
(c) Polymer (large r’s)

**Semiconductors** typically have smaller EO coefficients; one can also exploit the effects near a bandgap. We will describe those in nanowires.

**Electrooptic Modulator**

![Diagram of Electrooptic Modulator](image)

**MZM Optical Transfer Curve**

![Graph of MZM Optical Transfer Curve](image)
State-of-the-Art LiNbO$_3$ Externally Modulated Link

* Courtesy of Ed Ackerrman, PSI
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Electroabsorption Modulator

Franz-Keldysh Effect (FKE)  Quantum Confined Stark Effect (QCSE)

Bias and RF Signal

\[ \text{Bias and RF Signal} \]

\[ E_c \quad E_v \]

\[ \text{Franz-Keldysh Effect (FKE)} \quad \text{Quantum Confined Stark Effect (QCSE)} \]

\[ x \]

\[ p \quad i \quad n \]
Modulator DC photocurrent $I_m$ is caused by electroabsorption.

Optical Input

$P$

Optical Output

$I_m$

$i$

$n$
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Broadened optical absorption spectra of a quantum well

SQW Absorption (cm⁻¹)

Wavelength (nm)

E=30 kV/cm
50 kV/cm
70 V/cm
90 V/cm
130 V/cm
Design Strategy for achieving High Link Gain

\[
G = P_{opt}^2 \left[ \frac{\pi^2 t_{ff}^2 R_{in}}{V_{\pi}^2} \right] \cdot L_f^2 \cdot \left[ R_d^2 R_{out} \right]
\]

• To overcome the RC bandwidth limit with minimum reduction of the modulation efficiency.
• To achieve high RF link gain, high power operation with good coupling to fiber is needed.
• Low optical residual propagation loss to ensure small insertion loss.
• Large optical/microwave field interaction volume to ensure low \( V_{\pi} \), hence high RF link gain.
Intra Step Quantum Well (IQW)

Electric field

F = 140 kV/cm

F = 100 kV/cm

F = 200 kV/cm

Electroabsorption Spectrum

Transfer curve

Link gain vs. Opt. Power

Source: 1543nm, 10 mW
Loss=-12.4dB @0V
By placing the active absorption layer in the evanescent portion of the optical mode, we can decouple the optical waveguide design & electroabsorption material design.
Confinement factor $\Gamma$: the ratio of optical power within the active absorption layer.

- Smaller confinement factor
- Larger optical mode
- Smaller scattering loss
- Decoupling between optical and microwave waveguide
Reducing Insertion Loss

- Large optical mode improves fiber to EAM coupling to be around 2 dB per facet;
- Submerged mode reduces scattering loss;
- Small confinement factor reduces propagation loss with best result of 0.8 dB/mm;
- Best fiber-to-fiber loss was measured to be 4 dB.
Absorption along EAM Waveguide

EAM Waveguide Absorption Profile

Normalized Absorption Coefficient $\Gamma L = 7$
PCW EAM Waveguide Design
Peripheral Coupled Waveguide EA modulator

\[ W_1 = 1.5\mu m, \ W_2 = W_1 + 4\mu m \]

\[ W_1 = 2\mu m, \ W_2 = W_1 + 4\mu m \]

\[ W_1 = 2\mu m, \ W_2 = W_1 + 8\mu m \]

Confinement factor. = 2.64% 4.26% 3.44%

Propagation loss = 0.97dB 2.09dB 1.43dB

(length = 1.2 mm)
Fabricated PCW EAM
High Power EAM

Link gain higher close to transparency

Link Gain vs. Optical Power

EAM Optical Transfer Curves

590 mW input optical power
222 mA photocurrent
Gain Limitation of EM modulator

Analog fiber link

Small-signal Equivalent circuit of EA Modulator: Effect of Modulator Photocurrent
The modulator photocurrent at the biasing point is given by:

We can define an effective small-signal ac photocurrent resistance $R_P$:

$$R_P = \frac{2V_{\pi e}}{p_L t_1 \eta_M \pi}$$

It is seen that as power go up, $R_P$ decrease in value, therefore the link gain saturates under high power, reaching a limit independent of power or $V_{\pi e}$:

$$G \propto \left[ \left( \frac{p_L}{V_{\pi e}} \right)^2 \right] \left[ \frac{1}{1 + \frac{1}{R_P} \left( \frac{R_M}{R_L + R_S} \right)} \right]^2 \quad \rightarrow \quad G_{\text{Limit}} = \left( \frac{t_0 \eta_D}{\eta_M} \right)^2 \frac{4 \frac{R_D}{R_S}}{\left( 1 + \frac{R_M}{R_S} + \frac{R_M}{R_L} \right)^2}$$
Gain Saturation

G. E. Betts et al., PTL, 2006
Modulator Input Impedance

\[ R_L \] (modulator termination resistance)

\[ \eta_D = 0.8 \text{ A/W} \]
\[ t_i = t_o = -2 \text{ dB} \]
\[ \eta_M = 1 \text{ A/W} \]
\[ R_L = 50 \, \Omega \]
\[ R_M = 5 \, \Omega \]

As photocurrent becomes large, input impedance approaches modulator series resistance \( R_M \)

\[ \eta_M = 0 \text{ (no photocurrent)} \]
\[ \eta_M = 1 \text{ A/W (typical)} \]
\[ \eta_M = 0.1 \text{ A/W} \]
Experimental Verification of Photocurrent Effect

$\eta_M = 0.8 \text{ A/W}$
$\eta_D = 0.8 \text{ A/W}$
$t_i = t_O = -3 \text{ dB}$
$V_\pi = 0.85 \text{ V}$

*Measured gain closely matches gain from model.*
Possible solutions:

1. Blue shift Quantum Confined Stark Effect:

   Red-shift (regular) QCSE EAM: positive equivalent resistance
   Blue-shift QCSE EAM: negative equivalent resistance

\[
g = \left[ \frac{p_{lt} t_0 \eta_d \pi}{2V_{\pi}} \right]^2 R_D R_L \left[ \frac{4R_L R_S}{(R_L + R_S)^2} \right] \left[ 1 + \frac{p_{lt} \eta_M \pi}{2V_{\pi}} \frac{1}{R_M + \frac{R_L R_S}{R_L + R_S}} \right]^2
\]
Pre-biased quantum well structure for blue-shift QCSE

\[
\text{InP} \quad \text{InAs}_{0.4}\text{P}_{0.6} \quad \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \quad \text{InP}
\]

55 A 35 A

2. By reducing the photocurrent generates inside the QWs.

This can be done via “defects”, or by enhancing the probability that electrons and holes can combine through localization.
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Linearity of Analog Fiber-Optic Link: Two-tone SFDR

Analog Fiber-Optic Link

\[ f_1, f_2 \]

\[ 2f_1 - f_2, 2f_2 - f_1 \]

3rd Order Intercept Point and SFDR

- Fundamental Signal
- 3rd Order Intermodulation Distortion

Output RF Signal (dBm)

Input RF Signal (dBm)

OIP3
SFDR
Noise Floor
IIP3
EAM as a Negative Feedback System at High Power

\[
P_L t_P t_O [T(V_B) - T(V_B + V_M)]
\]

\[
(R_S + R_M) \eta_M / t_O
\]
**Electronic Negative Feedback System**

\[
\frac{V_{out}}{V_{in}} = \frac{G}{1 + fG}
\]

If \(fG \gg 1\), then

\[
\frac{V_{out}}{V_{in}} \approx \frac{1}{f}
\]

**EAM Link with Photocurrent Feedback**

\[
G = \frac{P_L t_1 t_O \eta_D \pi}{V_{\pi \epsilon}} \frac{R_L}{R_L + R_S} \sqrt{R_D R_S}
\]

\[
f = \frac{(R_S + R_M) \eta_M}{2 \eta_D R_D t_O}
\]
SFDR improves even as the modulator saturates

\[ \text{IIP2} \propto \left( \frac{dT}{dV} \right)^2 \propto k^4 \]

\[ \text{IIP3} \propto \frac{dT}{dV} \left( \frac{d^3T}{dV^3} \right) \propto k^3 \]

\[ \text{SFDR} \propto k^{4/3} \]

where

\[ k = 1 - P_L t_I t_P \eta_M \left( R_S + R_M \right) \frac{dT}{dV_M} = 1 + \frac{P_L t_I t_P \eta_M \left( R_S + R_M \right) \pi}{2V_\pi} = 1 + \frac{R_s + R_m}{R_P} \]
High Power EAM Linearity Analysis (cont’d)

SFDR of 135 dB/Hz^{2/3} at 700 mW
At 80 mW optical input power,
- Multi-octave SFDR of 118 dB-Hz$^{2/3}$, sub-octave SFDR of 132 dB-Hz$^{4/5}$.
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Electrooptic Coefficient

- Electrooptic effect:
  \[ \Delta \left( \frac{1}{n^2} \right)_{ij} = r_{ijk} E_k + s_{ijkl} E_k E_l \]

- Linear electrooptic coefficient, \( r \), of quantum dots:
  - \(^1\text{CdSe}\) (dispersed in polymer) \(\rightarrow\) 5-60 pm/V
  - \(^2\text{InAs}\) (grown on GaAs substrate) \(\rightarrow\) 243 pm/V
  - \(2\text{In}_{0.4}\text{Ga}_{0.6}\text{As}\) (grown on GaAs substrate) \(\rightarrow\) 25.8 pm/V

- QD systems exhibit 1-2 orders of magnitude enhancement over bulk electrooptic coefficient, due to quantum confinement effects and surface effects

- In the same token, it would be of much interest to examine the electrooptic coefficient of nanowires

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InP Nanowire Growth

1) Heat Sample in MOCVD reactor under PH$_3$ flow
2) Start TMIn flow
3) Indium droplets form
4) Nanowire begins to grow
Optimized Growth

- $T_g = 450 \, ^\circ C$
- $V/III \approx 25$

Very uniform diameter, length

High density ($\sim 10^9$ NWs/cm$^2$)
Measurement Results

<table>
<thead>
<tr>
<th></th>
<th>Diameter (nm)</th>
<th>Fill Factor</th>
<th>$r$ (pm/V)</th>
<th>$n^3r$ (pm/V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>InP NW</td>
<td>24 – 50</td>
<td>0.83 – 4.50 %</td>
<td>31 – 147</td>
<td>1010 – 4817</td>
</tr>
<tr>
<td>Bulk InP</td>
<td>N/A</td>
<td>N/A</td>
<td>1.53</td>
<td>50</td>
</tr>
<tr>
<td>Bulk LiNbO$_3$</td>
<td>N/A</td>
<td>N/A</td>
<td>$r_{33} = 34.1$, $n_e = 2.14$, $n_o = 2.22$</td>
<td>$n_e^3r_{33} - n_o^3r_{13} = 222$</td>
</tr>
</tbody>
</table>

- NW electrooptic coefficient exhibits an enhancement of 1-2 orders of magnitude over bulk InP

- Largest figure of merit is 20 times larger than LiNbO$_3$

- This fabrication technique provides a method to transfer a layer of aligned NWs to a host substrate.

- A waveguide with embedded NWs could provide adequate phase modulation.
Conclusion

• Major advances in link gain has been made in links using lithium niobate MZM modulator
• The electroabsorption modulator (EAM) can be designed to have low optical loss and high power properties
• The RF link gain using EAM saturates due to the photocurrent feedback effect which may be alleviated using blue shifted QCSE; or by reducing the photocurrent generated.
• Nonetheless, electroabsorption modulators can achieve high SFDR due to the same feedback effect.
• InP nanowires have great potential for effective electro-optic modulation.
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