More discussion on integrated waveguide modulators and switches

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Outline

• Fiber optic advantages
• Direct vs. external modulation
• Characteristics of electroabsorptive & electro-optic modulators
• Electro-optic waveguide polarization controller
• Requirements on optical switches
• Reliability requirements of integrated optical devices
Fiber optic communications

We live in the age of information, but how do people get their information?

- Computers
- Telephones
- FAX machines
- Cell phones

First and last miles, low bandwidth (MHz)

Local area network
Telephone exchange
Wireless base station

Thousands of miles
High bandwidth 10s GHz

Information carried by thousands of miles of glass fiber
Copper and wireless in the last mile

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Conversion between electrical and optical signals

Need devices for the conversion between electrical and optical signals
Optical-to-Electrical: Optical receiver -> Photodetectors (EE 533)
Electrical-to-Optical: Optical transmitter -> Integrated waveguide modulators
Why optical fiber? (Why not electrical cable?)

- Bandwidth
  - CAT 5 cable ~ MHz
  - Typical coaxial cable ~ GHz
  - Typical optical fiber > 10 THz

- Attenuation (signal loss) per km
  - CAT 5 cable ~ 75 dB @ 10 MHz
    \[ \text{Only good for } \sim 100 \text{ m} \]
  - Typical coaxial cable ~ 130 dB @ 500 MHz
  - Typical optical fiber ~ 0.2 dB, independent of frequency
    \[ \text{Good for } \sim 100 \text{ km} \]

\[
\text{dB} = -10 \log_{10} \left( \frac{\text{Output Power}}{\text{Input Power}} \right)
\]

\[10\% = 10 \text{ dB}\]
\[1\% = 20 \text{ dB}\]
\[0.1\% = 30 \text{ dB}\]
Fiber optic communications

Optical Transponder

Local area network
Telephone exchange
Wireless base station

Transmitter
Receiver

Optical signal

Transmitter
Receiver

Local area network
Telephone exchange
Wireless base station
Optical transponder
Different methods to modulate light

- To modulate -> encoding pulses of light to carry information bits

- Direct modulation: turn the light source on/off electrically

- External modulation: light source always on, external shutter to generate signal pulses

A British WWI signal light
In fiber optics …

Light source is a semiconductor laser diode with fiber output

Direct modulation of semiconductor laser

- Simple and cheap
- Low speed
- Wavelength changes with drive current
- Large wavelength excursion at leading and trailing edges of pulses
- Only used in low bandwidth short distance transmission
External modulators

- Leave the laser on all the time – stable wavelength
- Use external modulator to encoder information
- Modulator is a single-pole single-throw optical switch

There are two major types of external modulators:
- Electroabsorptive modulator
- Electro-optic modulator
Electroabsorptive modulator

Typically 2 V of on/off voltage, 6-10 dB on/off ratio, up to 40 GHz bandwidth.

Ideal for single-chip integration with laser diodes!
Challenge is to precisely match the absorption edge with laser wavelength.

Fig. 2. Ridge-waveguide configuration of the integrated device consists of a DFB laser and an EAM.
With Extinction Comes Dynamic Chirp

Any change in absorption also changes index

\[ \Delta \alpha(\lambda, V) \rightarrow \Delta n(\lambda, V) \]

which changes the phase during transmission

\[ \Delta \phi = 2\pi \Delta n L_{\text{mod}} / \lambda \]

which dynamically chirps the frequency during signal rise/fall

\[ \Delta \omega = \frac{d\Delta \phi}{dt} = \frac{2\pi L_{\text{mod}}}{\lambda} \frac{d\Delta n(V)}{dV} \frac{dV}{dt} \]

What does this mean to a fiber optic telecom system?
Pulse broadening due to chirp

Optical fiber has dispersion – light of different frequency travels at slightly different speed (typical fiber dispersion=16-19 ps/(nm*km) )

Chirped pulse has a large range of frequency

Pulse will spread after propagating in the fiber

Data pulses will merge and error of the communication will increase
Electro-Optic Modulator

A device to encode information on optical waves for fiber optic transmission. A key component in telecom and optically feed phased array antennas.
Electro-optic modulator

\[ E(t) = E_0 \cos(\omega t) \]

\[ I(t) = \langle |E(t)|^2 \rangle = |E_0|^2 \]

\[ \frac{E_0}{\sqrt{2}} \cos(\omega t - \phi_1) \]

\[ \frac{E_0}{\sqrt{2}} \cos(\omega t - \phi_2) \]

\[ E(t) = \left[ \frac{E_0}{\sqrt{2}} \right] \left[ \cos(\omega t - \phi_1) + \cos(\omega t - \phi_2) \right] \]

\[ = \left[ \frac{\sqrt{2}E_0}{2} \right] \cos(\omega t - (\phi_1 + \phi_2)/2) \cos((\phi_1 - \phi_2)/2) \]

\[ I(t) = 2|E_0|^2 \cos^2((\phi_1 - \phi_2)/2) \]

\[ \phi_1 = \pi \frac{V_1}{V} \]

\[ \phi_2 = \pi \frac{V_2}{V} \]

on-state

50 % on

off-state

How to introduce the phase shift?

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Electro-optic effect

- Change of index of refraction by applied E-field
- Linear (Pockels) EO effect
  \[ n(E) = n - \frac{1}{2} n^3 rE \]
- Quadratic (Kerr) EO effect
  \[ n(E) = n - \frac{1}{2} n^3 sE^2 \]
- In general Linear EO effect is much stronger than quadratic effect
- Most EO devices are based on linear EO effect
Typical linear EO materials

- Most of them are crystals
  \( \text{LiNbO}_3: r=34\times10^{-12} \text{ m/V} \)
  \( n=2.2, \varepsilon_r=28 \)

- EO polymers – artificially designed and synthesized through chemistry and molecular engineering
  \( r=300\times10^{-12} \text{ m/V} \)
  \( n=1.7, \varepsilon_r=3 \)
Speed match and modulator bandwidth

Speed matched case

Speed mismatched case

Voltage

Optical phase

High and sharp pulse

Low and broadened pulse
Amount of modulation is determined by mismatch and frequency

\[ E(x,t) = E_0 \cos(k_0 x - \omega t) \]

When speed is mismatched, relationship between modulation and frequency \( \omega \) follows a sinc function
Modulator bandwidth

Bandwidth of an EO modulator is defined as the frequency at which
\[
\left| (\sqrt{\varepsilon_r} - n) \frac{2\pi}{c} fL \right| = \frac{\pi}{2}
\]

- inversely proportional to the speed mismatch

\[
BW = \frac{c}{4L|\sqrt{\varepsilon_r} - n|}
\]

Comparison between LiNbO3 and polymer using a 2 cm long modulator

LiNbO3: \( \varepsilon_r = 28, \quad n = 2.2 \). \( \sqrt{\varepsilon_r} - n \) = 3.09, \( BW \) = 1.2 x 10^9 Hz = 1.2 GHz

EO polymer: \( \varepsilon_r = 3, \quad n = 1.62 \). \( \sqrt{\varepsilon_r} - n \) = 0.11, \( BW \) = 3.4 x 10^10 Hz = 34 GHz
Electro-Optic Polymer

Polymer materials whose indices of refraction vary with external electric fields

• Non-linear chromophores embedded in a polymer matrix

• When chromophores are aligned through poling, the polymer material exhibits strong EO effect
EO polymer modulator

- EO polymer WG
- Lower cladding
- Ground electrode
- Substrate
Frequency Response

Packaged EO polymer modulator on flexible substrate

Optical response at 105.8 GHz

Optical response curve from 74 to 113 GHz. The total variation is less than 3 dB.

Frequency response beyond 110 GHz
Polarization mode dispersion (PMD)

**Ideal fiber:** Pulse propagation independent of polarization

**Real fiber:** Small birefringence
- Two principle states of polarization (PSP)
  - Propagation speed differs between PSP’s
  - Two copies of pulses overlaid at receiver
    - (1\textsuperscript{st} order PMD)
    - \( \Rightarrow \) ISI
Device function

- Convert any input SOP into any output SOP
- Key component in PMD compensators
- Important for fiber optic transmission systems

Schematic diagram of a PMD compensated receiver
Principle of operation

A set of voltage-controlled quarter waveplates in lithium niobate waveguide that can rotate endlessly. Constant retardance. Continuous and endless adjustable orientation

Free space schematic  LiNbO$_3$ waveguide device
Electrically controlled waveplate

A waveplate with phase shift of $\tau$ oriented at $\alpha$, where

$$\tau \approx \frac{2\pi}{\lambda} L_{\text{act}} \sqrt{[(n_{\text{TE}} - n_{\text{TM}}) + r_{22} n_o^3 E_y]^2 + (r_{22} n_o^3 E_x)^2}$$

$$\tan(2\alpha) \approx -\frac{r_{22} n_o^3 E_x}{(n_{\text{TE}} - n_{\text{TM}}) + r_{22} n_o^3 E_y}$$

In order to get a quarter waveplate oriented at $\alpha$, the voltages applied to the device are

$$V1 = Vt(90) + Vt(0) + Vqwp(0)\cos(2\alpha) + Vqwp(90)\sin(2\alpha)$$

$$V2 = Vt(90) - Vt(0) + Vqwp(0)\cos(2\alpha) - Vqwp(90)\sin(2\alpha)$$

Four characteristic voltages: $Vt(0)$, $Vt(90)$, $Vqwp(0)$, and $Vqwp(90)$ for each waveplates

Common voltages $Vt(90)$ and $Vqwp(90)$ produce $E_x$, differential voltages $Vt(0)$ and $Vqwp(0)$ produce $E_y$.
$Vt(0)$ is the DC bias voltage that compensate for $n_{\text{TE}} - n_{\text{TM}}$. If $Vt(0)$ is incorrect, both retardance and orientation will be smaller.
Conversion of states of polarization

Laser → Control Electronics → Polarization Controller under Test → HP Polarization Analyzer

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N x N optical switch array

- Most basic switch elements are 1 x 2 and 2 x 2
- To make an N x N switch network an array of basic switch elements are needed

Major requirements

- **Full connectivity**
  - any input can be connected to any output

- **Non-blocking**
  - Existing connections do not prevent new connections between unused inputs/outputs

- **Low insertion loss**
  - Needs to be path independent too

- **Low crosstalk between output ports**

- **Polarization/wavelength insensitive**
  - Performance is not affected by polarization and wavelength

- **Fast switching speed**
Full connectivity

Consider two 4x4 switches built with 2x2’s. Each 2x2 element can be either in bar state or cross state.

Bar State

Cross State

This 4 x 4 switch does not have full connectivity. Input 1 can only be connected to outputs 1, 2, and 3.

Still use the same 2x2’s, this architecture has full connectivity. Any input can be connected to any output.

However, it is not “non-blocking”.

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Non-blocking means any free inputs can be connected to any free outputs. Existing connections do not “block” any new connections.

When input 1 -> output 1, input 2 can only be connected to output 3 or 4.

1->1 connection “blocks” 2->2 connection.

Adding another stage makes the switch array non-blocking.
Path dependent loss

Connection 1 -> 4 goes through 7 switch elements – High loss.
Connection 4 -> 1 goes through 1 switch elements – Low loss.
Polarization independent switching

Digital Y-switch elements in lithium niobate

- Polarization independent
- Broad optical bandwidth
- Large voltage tolerance
- No bias required
Elimination of PDL and PMD

- Device is built on 2 chips of equal length
- TE-TM conversion is made by a $\lambda/2$ plate
- The PDL & PMD of the first chip is cancelled by the second chip

<table>
<thead>
<tr>
<th>PDL (dB)</th>
<th>PMD (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No WP</td>
<td>2.5</td>
</tr>
<tr>
<td>With WP</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
</tr>
</tbody>
</table>
Switch Module Architecture

- Strictly non-blocking with signal bridge and dumping
- Crosstalk reduction and path loss equalization
- Reduction of control voltages by logic ganging
- Variable attenuators on EN 6X6 outputs

CR 4X8
- 6 columns
- 84 switch elements
- 32 control voltages

EN 6X6
- 9+1 columns. Internally a 12X6 fabric
- 240 switch elements
- 74 control voltages

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Field Test in MONET D.C. Network

- Switch Modules
- Circuit Pack
- Network Element Bays
  - 12 CR4X8's
  - 32 EN12X6's
- DARPA
- DSA
- DIA
- NSA
- NASA
- West Ring
- East Ring
- NRL

- Cross-Connect
- Add/Drop MUX
- Optical Amplifiers

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Packaging of integrated optical devices

• Challenges
  – Matching of size and numerical aperture of the fiber mode and waveguide mode
  – Small waveguide dimension requires precise alignment
  – The alignment needs to be stable/reliable over temperature and the lifetime of the device
• Most of the cost of fiber optic components is in the packaging
Electronic vs. optical packaging


- driver
- laser
- Bonding Pad
- Bonding wire
- 50 Ω CPW
- 8 µ core
- 5 µ x 0.5 µ Typical
- Must align precisely

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Mode match

Waveguide modes (~1 um) are usually much smaller than fiber mode (10 um)
• Tapered waveguide section to transform mode size
• Micro lens or lensed fiber

A lithium niobate modulator package

Packaging of LiNbO$_3$ Switch Modules

- 12-Fiber Ribbon
- MTP Connector
- Si V-Groove Fiber Array Attachment
- LiNbO$_3$ Chips
- Lead Frame
- Metal Package
- Lid to be Seam Sealed
- Halfwave plate
Facing the real world

• **Performance AND reliability**
  – System components have to maintain full performance specification over temperature range (Typ. 0-80 °C for EO modulators)
  – System components have to maintain full performance specification over the lifetime (Typ. 15-25 years at 60 °C for EO modulators)

• **Telecom industry reliability standards**
  – Telcordia GR-468 optoelectronic devices, GR-1221 for passive components

• **Defense industry has more stringent standards**
  – Mil-STD-883
Modulator reliability requirements

Telcordia GR-468-CORE

Section 10 (Modulator Reliability and Quality Criteria)

3 test categories
- Mechanical integrity (shock, vibration...)
- Endurance (temperature, accelerated aging...)
- Special tests (Electrostatic discharge protection...)

Minimum of 11 devices are required for each test.

0 failure is allowed.
### Required modulator reliability tests (1)

**... Table 24. Required Reliability Tests for External Modulators**

<table>
<thead>
<tr>
<th>HEADING</th>
<th>TEST</th>
<th>REFERENCE</th>
<th>CONDITIONS</th>
<th>SAMPLING&lt;sup&gt;a&lt;/sup&gt;</th>
<th>ENV'T</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LTPD</td>
<td>SS</td>
</tr>
<tr>
<td>Mechanical Integrity</td>
<td>Mechanical Shock</td>
<td>MIL-STD-883 Method 2002</td>
<td>5 times/axis 500 G, 1.0 ms</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Thermal Shock&lt;sup&gt;b&lt;/sup&gt;</td>
<td>MIL-STD-883 Method 1011</td>
<td>ΔT = 100°C 0°C to 100°C</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Solderability</td>
<td>MIL-STD-883 Method 2003</td>
<td>(steam aging not required)</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>Fiber Pull&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>Endurance</td>
<td>Accel. Aging&lt;sup&gt;d&lt;/sup&gt;</td>
<td>(R)-453 Section 5.18</td>
<td>70°C; max. spec. 2,000 hrs. 85°C; max. spec. 2,000 hrs.</td>
<td>—</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>High Temp. Storage</td>
<td>—</td>
<td>max. storage T 2,000 hrs.</td>
<td>—</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Low Temp. Storage</td>
<td>—</td>
<td>min. storage T 2,000 hrs.</td>
<td>20</td>
<td>11</td>
</tr>
</tbody>
</table>
### Required modulator reliability tests (2)

<table>
<thead>
<tr>
<th>HEADING</th>
<th>TEST</th>
<th>REFERENCE</th>
<th>CONDITIONS</th>
<th>SAMPLING&lt;sup&gt;a&lt;/sup&gt;</th>
<th>ENV’T</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LTPD</td>
<td>SS</td>
</tr>
<tr>
<td>Endurance</td>
<td>Temperature Cycling&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Section 5.20</td>
<td>-40°C to +70°C</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100 pass/fail</td>
<td>—</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>500 for info.</td>
<td>—</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-40°C to +70°C</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>500 pass/fail</td>
<td>—</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1,000 for info.</td>
<td>—</td>
<td>11</td>
</tr>
<tr>
<td>Damp Heat</td>
<td>MIL-STD-202</td>
<td>Section 5.23</td>
<td>85°C/85%RH 500 hrs or 50°C/85%RH, 5000 hrs.</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>Cyc. Moist. Res.</td>
<td>Sec. 5.23</td>
<td></td>
<td></td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>Special Tests</td>
<td>Internal Moisture&lt;sup&gt;b&lt;/sup&gt;</td>
<td>MIL-STD-883 Method 1018</td>
<td>max. 5,000 ppm water vapor</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>ESD Threshold&lt;sup&gt;d&lt;/sup&gt;</td>
<td>TR-870 Sec. 4.2.3</td>
<td></td>
<td>—</td>
<td>6</td>
</tr>
</tbody>
</table>

Notes:

a. LTPD (in %); min. acceptable sample size (SS) and corresponding number of allowed failures (C).

b. This is only required for hermetic packages.

c. If the module includes a fiber pigtail that will not be handled in the field installation. Otherwise, a 2 kg fiber pull test should be performed. The pull test of 0.5 kg is for polarization maintenance (PM) fiber pigtails.

d. The temperature is specified as the ambient temperature, which can be either the case or chamber temperature. Devices shall be biased and modulated at the max. operating specifications.

e. The supplier must provide test results, including failure analysis, for modules cycled to the number specified for information purposes. Either biased or unbiased T/C test is acceptable.

f. Lithium Niobate modulators are considered not sensitive to ESD. This test is not required if it was previously performed on similar devices.
Summary

• Optical fiber has superior loss and bandwidth
• External modulation excels at high speed
• Electroabsorptive modulator small but suffer from chirp
• Speed mismatch determines EO modulator bandwidth
• Optical switches need to meet many requirements
• Precise alignment makes packaging difficult
• Telcordia standard tests ensures reliability