Residual Amplitude Modulation of optical phase modulator
Outline

- Phase modulator description
- Definitions of the RAM issues
- Observations from experiment
- Interpretation and simulation
- Voltage induced reduction of the RAM
Introduction: Optical phase modulators

- Type of optical modulators currently produced
  - Intensity modulators (Mach-Zehnder)
  - I&Q modulators (Dual Mach-Zehnder)
  - Phase modulators

- Phase modulators widely deployed in fiber systems:
  - Telecom, Science, Sensing

- Examples of applications of phase modulators:
  - spectroscopy
  - frequency side band generation in cold atoms optics & atoms clock,
  - spectral broadening to prevent SBS in intense laser systems,
  - coherent beams combining
  - laser wavelength locking (Pound Drever Hall)
Phase modulator

- **Principle**
  - The phase of the optical carrier is modulated by an external voltage thanks to the electro-optic effect.
- **Most of the phase modulators are produced by use of the standard lithium niobate waveguide processes.**
  - Annealed Proton exchange or Titanium indiffusion
  - Lumped electrodes (low frequency <200MHz)
  - Travelling wave coplanar electrodes (High frequency 10-50GHz)
- Designed for any wavelength windows
  - from 780nm up to 2000nm.
- **Characterized by**
  - insertion loss (IL)
  - driving voltage ($V_\pi$)
  - modulation bandwidth (E-O BW)
  - Polarization extinction ratio (PER) or polarization dependent loss (PDL)
  - **Residual Amplitude Modulation (RAM)**
RAM / PIM

- Key parameter for some applications = Residual Amplitude Modulation (RAM).
  - RAM : residual amplitude modulation.
  - PIM : parasitic intensity modulation.
- RAM = ratio between the voltage dependent power modulation and the total average power transmitted by the phase modulator.

\[ P(t) = P_o + \varepsilon V(t) \]

- \( V(t) \): time dependent applied voltage
- Peak to peak RAM expressed by:

\[ RAM_{dB} = 10 \log_{10} \left( \frac{\varepsilon V_{pp}}{P_o} \right) \]

- RAM is expected to be close to zero in a perfect phase modulator,
- **There should be any RAM. Why is it not the case?**
- The goal:
  - to explain the main roots of the RAM
  - to prevent or to reduce the RAM
An obvious explanation: RAM induced by the remaining resonant cavity

- Tilted input and output facets of the waveguide behave as a weak optical resonator cavity:
  - A weak amplitude modulation should be observed at the output
  - Interferences occurring between the main guided wave and the parasitic reflected waves.

- The peak-to-peak RAM originated from the resonator is given by:
  \[ R_{AM_{db}} \approx 10 \log_{10} \frac{4R}{1 - R^2} \]

- \( R \) is the coefficient of reflection in power at the facet interface.

- \( R \): Fresnel reflection coefficient \( R_{\text{Fresnel}} \) and return coupling loss \( \eta(\alpha) \) from the I/O facets tilted by an angle \( \alpha \):

  \[ \eta(\alpha) = \exp\left[-\frac{n_e^2 \pi^2 \alpha^2 \omega^2}{\lambda^2}\right] \quad \quad R_{\text{Fresnel}} = \left(\frac{n_e - n_{\text{fib}}}{n_e + n_{\text{fib}}}\right)^2 \]

- Expected resonant cavity \( R_{AM} = 28-30 \text{ dB} \)

- \textbf{Is it the case?}

- \( \lambda_0 \) is the optical wavelength in vacuum (1.55\( \mu \)m)
- \( \omega_0 \) half diameter of the guided mode field (typ 3\( \mu \)m)
- \( n_e \) extraordinary refractive index of lithium niobate
- \( n_{\text{fib}} \) refractive index of silica fiber
- \( \alpha = 5.6^\circ \)
- \( \eta(\alpha) = 1.16 \times 10^{-2} \), and \( R_{\text{Fresnel}} = 3.24 \times 10^{-2} \), i.e. \( R \approx 1.2 \times 10^{-4} \).
Let us try with a 1060nm APE waveguide phase modulator

Conditions

- A peak to peak voltage of 20Vpp at 100kHz is applied to the modulator.
- The half wave voltage of the modulator is $V_{\pi}=2V$.

Observations

- Oscillating response of the RAM vs applied voltage.
- The amplitude of the fringes: not uniform,
- For $V<0$, the RAM reaches the expected value -28dB
- RAM from resonant cavity is predominant for $V<0$
- Amplitude of the fringes for $V>0$ reached an unexpected RAM of -21dB.
Question of technology: let us try at 1550nm on titanium indiffused waveguide phase modulator

- Phase modulator at 1550nm. Waveguide technology: titanium indiffusion
- Fringe pattern shows a contrast growing with the applied voltage, reaching 20dB of peak to peak RAM when V>0.
- Below -5V, only some fringes remain
- The corresponding halfwave voltage $V\pi$ of 2V can be explained by the residual resonant cavity
- RAM of the spurious oscillations, -30dB peak to peak agrees with expected value
- For V<0, it confirms the interpretation of a RAM produced by the residual cavity closed to the expected one.

**QUESTION:** what is the origin of the larger oscillations when V>0?
RAM: interpretation

- To take into account the voltage induced electro-optic index profile

\[ \Delta n(x, y) = -\frac{1}{2} n_e^3 r_{33} E(x, y) \]

- The electro-optic induced graded index is much wider than the doped optical waveguide (3-4µm in depth)
- Can be as high as 30-40µm
- The induced profile variation can be positive or negative depending on the sign of the electric field
- The area below the electrodes behaves as a large two-mode coupling section
Electro-optic induced waveguide profile

- Diffused waveguide

- The incoming wave can be coupled to the fundamental mode and to the electro-optically induced secondary mode.

- At the electrodes output, the two delayed waves can be coupled at the output fiber to interfere, producing undesired amplitude modulation.

- Let us try to simulate this!
Interpretation

- Simulations were carried out thanks to finite-difference Beam Propagation Method (FD-BPM) program.
- The gradient index profile induced by the electric field is taken into account and extends below the electrodes with a depth that can be as large as 40µm,
- Simulation shows that for a positive electric field an electro-optically induced amplitude modulation can be revealed.
- The corresponding peak-to-peak RAM increases with the positive applied voltage
- Decreases for negative applied voltage
- It confirms the experimental observations

- New experiments to confirm this.
New modulator characterization

Setup

- A 1550nm tunable laser light is launched into the waveguide.
- A low frequency modulation voltage is applied to the electrodes.
- A DC bias voltage is added to the electrodes.
- The detected signal is connected to an electrical spectrum analyzer.
- The response is recorded in order to display only the low level residual amplitude modulation.
- We plot the wavelength dependence to check the optical delay.
Wavelength Dependence

- Tunable External Cavity laser
  - $V_{\text{bias}} = +7\text{V}$
  - $P_{\text{opt}} = 0\text{dB}$
  - $L_{\text{elec}} = 40\text{mm}$
  - $\Delta n = 1.1 \times 10^{-2}$
  - Good agreement with
    
    $\Delta n = n_{\text{eff}}^{00} - n_{\text{eff}}^{10}$
    
    - Confirms the model of a two waves interferometer below the electrodes at positive voltage

\[
\Delta n = \frac{1}{L} \frac{\lambda_k \lambda_{k+N}}{\lambda_k - \lambda_{k+N}}
\]
Actual RAM measurement

- Measurement of RAM on 1530nm phase modulator vs the DC Bias applied voltage.
Conclusions

- Only resonant cavity modulation cannot solely explain the RAM effect.
- Additional DC bias reveals difference of behavior of the RAM depending on the sign of the additional DC voltage.
- RAM can be explained, thanks to a model of an electrically induced waveguide.
- RAM is produced below the electrodes by a parasitic interferometer and mode coupling.
- A simple FD-BPM model allows to reproduce the RAM behavior at the modulator output vs the DC bias voltage.
- Residual amplitude modulation can be strongly reduced thanks to a permanent DC voltage corresponding to a global negative index variation, cancelling out the deep electrical induced waveguide.
- Low permanent DC voltage (5-15V) is enough to reduced RAM by more than 10dB, compared to an unbiased modulator.