High-speed Control of Lightwave Amplitude, Phase, and Frequency by Use of Electro-optic Effect

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**Introduction**

- **Lightwave**
  
  \[ E = A \cos(2\pi f_0 t + \varphi) \]

- **Modulation**
  
  Process of varying properties \((A, f, \varphi)\) of periodic waveform to match the transmission channel

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**Diagram:**
- **Data Signal**
- **Optical Modulator**
- **Channel**

**Steps:**
- PM
- MZM
- SSB, FSK
- High-order Sideband Generation
1. PM

- **Principle : EO (Electro→Optic) effect**
  - Electric Voltage → n ↑ → phase of lightwave ↓
  - Using EO material: Lithium niobate (LN), lutum tantalite (LT), gallium arsenide (GaAs)

- **Optical Output (R)**
  - \[ R = A^{LW} e^{2\pi i f_0 t + i f(t)} , \quad f(t) = KV(t) \]
  - If f(t) is a sinusoidal signal,
    \[ R = A^{LW} \exp i[2\pi f_0 t + A^{RF} \sin 2\pi f_m t] \]
    \[ = A^{LW} \sum_{n=-\infty}^{\infty} J_n(A^{RF}) \exp 2\pi i[f_0 t + n f_m t] \]
  - \[ R = A^{LW} \exp i[2\pi f_0 t + A^{RF} \cos 2\pi f_m t] \]
    \[ = A^{LW} \sum_{n=-\infty}^{\infty} i^n J_n(A^{RF}) \exp 2\pi i[f_0 t + n f_m t]. \]

- **Fig. 1. Optical Phase Modulator**
- **Fig. 2. 1st kind of Bessel function**

- **Symbols**
  - \( A^{LW} \): optical transmittance
  - \( f_0 \): optical carrier
  - \( A^{RF} \): index for optical phase deviation induced by electric signal
  - \( J_n(A) \): 1st kind n-th order Bessel function
  - \( V(t) \): electric voltage on the electrode
2. MZM (1)

- **Principle : MZ Intensity Modulator(EO effect)**
  - A pair of E-signal → 2-PM, balanced push-pull operation
  - 3-type
    - $A$: induced phase of modulator
    - $g(t)$: optical phase difference between two arms of MZM
    - C–axis: directed at x,z axis in x,z cut LN substrate

- **Output intensity (IRI)**
  - $|R| = \frac{1}{2} \left| \left( e^{i(g(t)/2)} + e^{-i(g(t)/2)} \right) e^{2\pi ifo t} \right|
  - $= |\cos [g(t)/2]|$. 

- **ON/OFF switching by changing V(t)**

Fig.3. MZM

Fig.4. Cross sections of MZM for push-pull operation

Fig.5. Intensity Modulation using MZM
2. MZM (2)

- **In practical**, Ref.[31]  
  - **ER**: Extinction Ratio
  - **Problem**: Imbalance in 2-arms, High-order radiative wave $\rightarrow$ ER↓
  - **Solution**: Active trimmer

- Bias control with 3 – Electrodes
- Trimmer compensates problem $\rightarrow$ ER↑

- **Output**
  \[ R = \frac{1}{2} A^1 e^{2\pi i f_0 t} \left( e^{i(A_RF \sin 2\pi f_m t + \phi_B)/2} + e^{-i(A_RF \sin 2\pi f_m t + \phi_B)/2} \right) = A^1 e^{2\pi i f_0 t} \cos \frac{\phi_B}{2} \sum_{n=-\infty}^{\infty} J_{2n}(A_{RF}) e^{2\pi i (f_0 + 2nf_m) t} + i \sin \frac{\phi_B}{2} \sum_{n=-\infty}^{\infty} J_{2n+1}(A_{RF}) e^{2\pi i (f_0 + (2n+1)f_m) t} \]

- **Application**: DSB-SC Modulation
  - Add sinusoidal signals to Electrode C $\rightarrow$ Null-point at C
  - generation DSB(USB & LSB) components
  - Imperfection of MZM fabrication, electric circuits problem $\rightarrow$ Use Trimmer

- **DSB-SC**: Double-sideband Suppressed Carrier
  - $\phi_B$: DC bias
  - $f_0$: Input optical frequency
  - $f_m$: Input RF signal frequency
  - USB(Upper sideband), LSB(Lower sideband)
  - Two-tone lightwave generation $f_0 - f_m$ $f_0$ $f_0 + f_m$

Fig.6. Degradation of ER
Fig.7. High ER Intensity modulator using active trimmers
Fig.8. After trimmer
Fig.9. DSB-SC signal w/w/o trimmer
Fig.10-11. w/, w/o trimmer
3. SSB, FSK Modulator (1)

**SSB Principle** Ref.[13,14]
- 2-MZM, RF<sub>A,B</sub>, DC<sub>A,B,C</sub>

![Fig.13. Optical SSB Modulator](image)

- RFA, RF<sub>B</sub> : traveling wave electrodes for high speed operation
- DC<sub>C</sub> : main MZ has an electrode for dc-bias

- **Key**
  - Path 1 : \( \cos(\theta + \phi) / 3 : \cos(\theta + \pi) \)
  - Path 2 : \( \cos(\theta + \pi/2) / 4 : \cos(\theta + 3\pi/2) \)

- **Path 1,2,3,4** : null-bias → \( e^{2\pi if_{ot}} \)
- Amplitude of LSB / USB
  - \( \frac{1 + je^{j\phi_{FSK}}}{2} / \frac{-1 + je^{j\phi_{FSK}}}{2} \)

- \( \phi_{FSK} \) : Induced phase difference at DC<sub>C</sub>

**SSB Output**
- \[ R = \frac{e^{2\pi if_{ot}}}{4} \sum_{j=1}^{4} \sum_{n=-\infty}^{\infty} J_n(A^{RF}_{j})e^{i(2\pi f_m t + \phi_{RF}_{j})} A^{LW}_{4} e^{i\phi_{LW}} \]
- \( A^{LW} e^{2\pi if_{ot}} [J_1(A^{RF})e^{2\pi if_{ot}} - J_3(A^{RF})e^{-3\pi if_{ot}}] \)

- Phase difference of RF signal ↔ Lightwave
  - ① 90° : USB
  - ② - 90° : LSB

![Fig.15. SSB Modulation case of USB](image)
SSB using Optical Hilbert Transform

1) Make DSB by using 1-MZM

2) Power splitter
3) Up-line : pass trough
4) Down-line : Make OPS (Optical Phase-shifter) + OFHT (Optical Fractional Hilbert Transformer)

A) $\theta = 90^\circ$ : USB

B) $\theta = -90^\circ$ : LSB

$$H_{FHT}(\omega) = \begin{cases} e^{-j\omega}, & \omega > \omega_c \\ 0, & \omega = \omega_c \\ e^{j\omega}, & \omega < \omega_c \end{cases}$$
3. SSB, FSK Modulator (2)

**FSK Principle** Ref.[9,10]
- FSK Concept

![FSK modulated signal](image)

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**Why not DCc but RFc?**
- RFc is faster than DCc because DCc’s switching time is limited by electrode response in high speed operation

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**FSK Modulator** Ref.[11,13]
- Principle

![Fig.14. Optical FSK Modulator](image)

- RFₐ, RFₐ : null-point, dc-bias is controlled by RFₐ,RFₐ
- RFc : make 90° phase difference → SSB
3. SSB, FSK Modulator (3)

- **Application (1):** FSK/SSB Modulator (SSB-SC) & 40GHz Optical frequency shift
  - Experiment Ref.[9,13,14,32]

- Suppress input optical carrier and make SSB-SC
- Convertible into USB or LSB by changing bias at MZc

![Z-cut dual-electrode FSK/SSB Modulator](image1.png)

![FSK Modulation setup using z-cut FSK/SSB Modulator](image2.png)

- Modulator 3dB BW: 30GHz
- Insertion loss: 4.2dB
- Modulation Frequency: 40GHz
- NRZ PRBS 40Gbps data signal to C1

![Optical spectra of z-cut FSK/SSB Modulator](image3.png)

![Overall band spectra](image4.png)

![Demodulated FSK Signal & Eye pattern](image5.png)
Application (2) : 80Gbps DQPSK Modulation  Ref.[4,19,20,32]

- DQPSK Concept
  - Optical 3dB BW of each electrode : 27GHz
  - Insertion loss : 5.1dB
  - Modulation Frequency : 40GHz
  - NRZ PRBS 40Gbps data signal (10Gbps for each channel x 4)

1-bit delay’s constructive/destructive ports were connected to balanced PDs.
80Gbps transmission success

- $\Delta \phi$ : differential optical phase of 1-bit interferometer
- B2B : Back – to - Back

Fig.24. DQPSK using z-cut FSK/SSB Modulator

Fig.25. Spectrum of 80Gbps optical DQPSK

Fig.26-27. Eye diagram of DQPSK signal and Optical B2B BER curves
4. High-order Sideband Generation (1)

- **High-order sideband** Ref.[19,20]
  - Using harmonics: \( f_0 + Nf_m \)
    - \( N \): N-th order of harmonics

- **Why High-order?**
  - Upper limit of \( f_m \) depends on transmission loss in travelling wave electrodes in MZM
  - \( f_m < 50\text{GHz} \) → use harmonics of \( f_m \) which can make higher frequency components

- **Application (1) : QDSB-SC**
  - QDSB-SC: Quadruple DSB-SC
  - \( f_m \): modulating frequency, 10.5GHz
  - Carrier suppression ratio: 45.8dB
  - Spurious suppression ratio: 41.8dB
  - Make 42GHz millimeter wave

- Advantage of QDSB-SC
  - More Robust in Vibration, Temperature than mode locking, LO-mixing, etc.

- Disadvantages of QDSB-SC
  - Small modulation efficiency (use of nonlinearity of Modulator)
4. High-order Sideband Generation (2)

- **Application (2) : ROM** Ref.[21-24,34-36]
  - Reciprocating Optical Modulation
  - Recycling sideband components → High power (overcome QDSB-SC’s small signal)
  - 2-FBG + 1-PM

- **Reciprocate** (왕복운동을 하다)
  - RF signal frequency = 39.06GHz

- Can make up to 8th order LSB 312.48GHz
- Spectral components in ROM are stationary phase-locked to each other without PLL
Conclusion

Summary

- **Intensity**
  - IM, OOK

- **Phase**
  - EO Effect $\rightarrow$ PM, MZM
  - Application: DSB-SC Modulation

- **Frequency shift**
  - SSB, FSK
  - Application: FSK/SSB Modulation (=SSB-SC)

- **High-order**
  - High-order Sideband Generation
  - Application: QDSB-SC Modulation, ROM
Q & A

THANK YOU :)

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