Development and Enabling Technologies of Hybrid Access Networks

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Acknowledgement

- Chun-Ting Lin, Po Tsung Shih, Sheng-Peng Dai, Wen- Jr Jiang ,Peng-Chun Peng, Wen-Qiang Xue, Er Zih Wong and Yen-Lin Ho

The highest mountain a vehicle can reach at Taiwan: 3275 m

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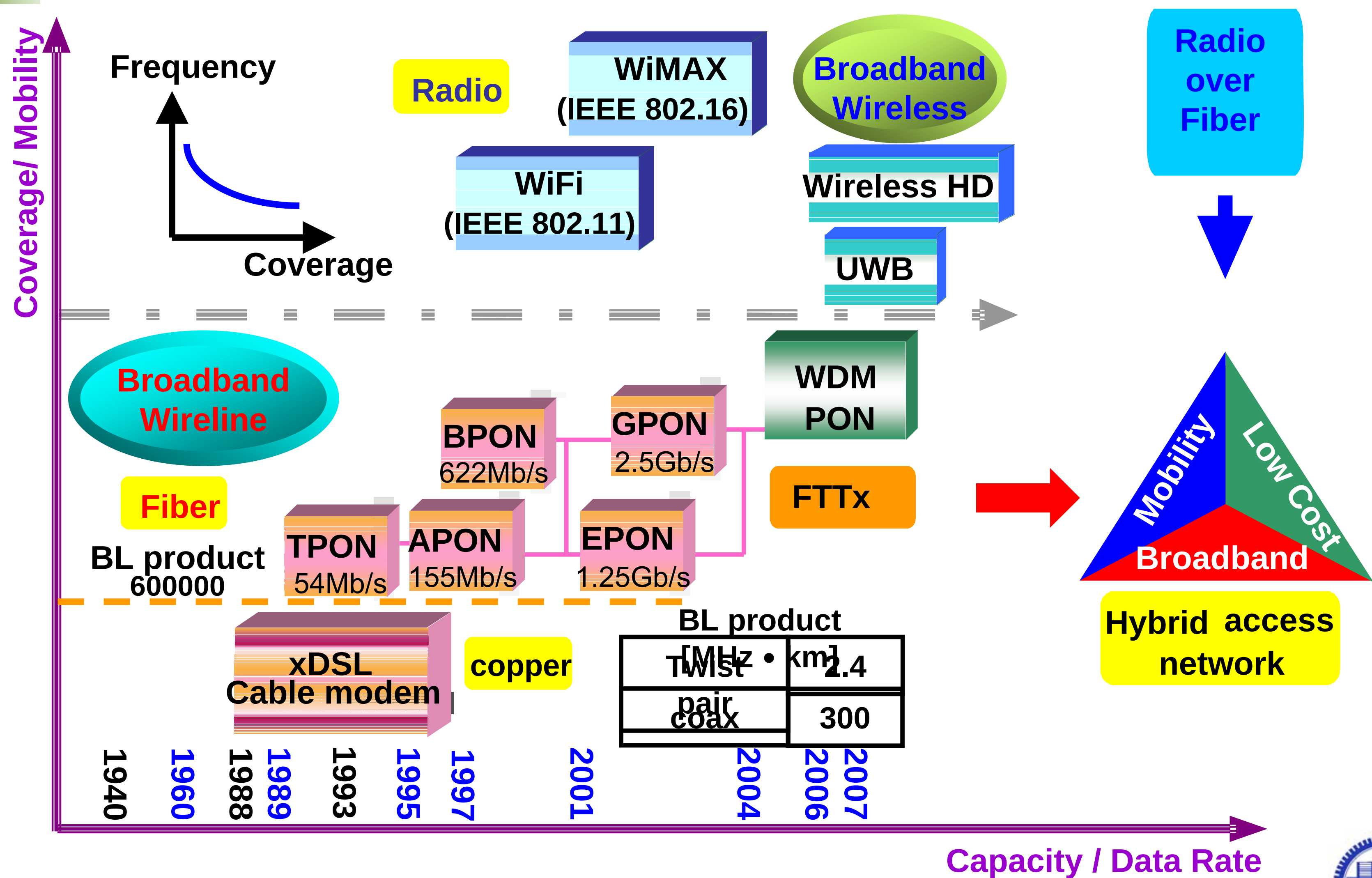
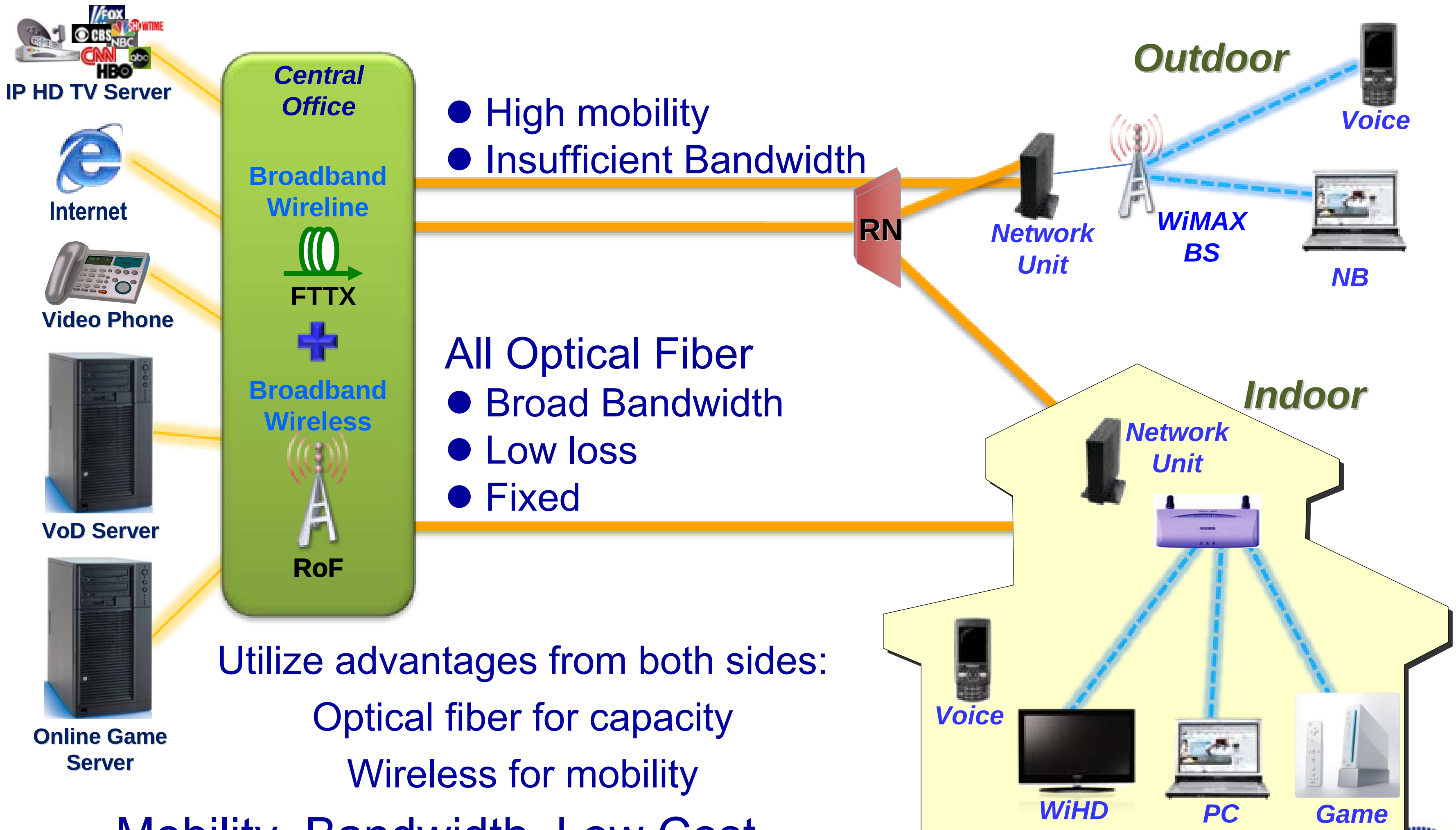
Outlines

- Reviewed the development of access networks
- The emerging of hybrid access networks
- To provide seamless integration between optical and wireless system
  - High spectral efficiency modulation format
    - Limited available bandwidth of wireless spectrum
    - Avoid format conversion at base station
    - 18 Gb/s, 64-QAM remote heterodyne OFDM-RoF system
  - A cost-effective millmeter-wave up-conversion scheme (60 GHz wireless HD services, IEEE 802.15 WPAN)
    - Frequency quadrupling and octupling techniques
- Conclusions

Development of Access Networks



Hybrid Access Networks



- High mobility
- Insufficient Bandwidth

All Optical Fiber
- Broad Bandwidth
- Low loss
- Fixed

Utilize advantages from both sides:
Optical fiber for capacity
Wireless for mobility

Mobility, Bandwidth, Low Cost

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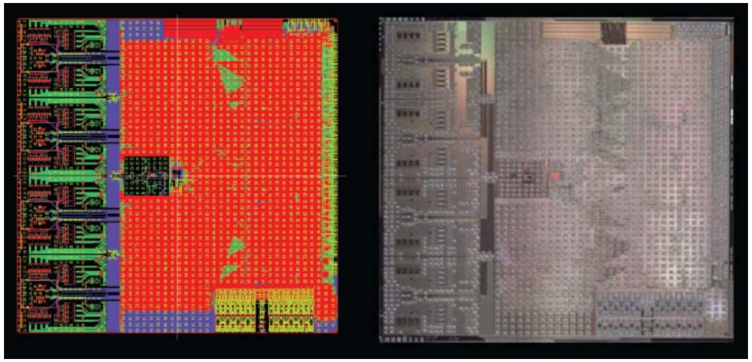
Advantages of OFDM Modulation Formats

- OFDM is a simple solution to signal dispersion and multi-path interferences, first proposed in 1960
  - Multi-carrier modulation format
  - Increased efficiency because carrier spacing is reduced (orthogonal carriers overlap)
  - Equalization simplified
  - More resistant to fading
  - Now possible because of advances in **signal processing horsepower**
- Disadvantages of OFDM
  - Higher **peak-to-average power ratio** (PAPR) ⇨ IMD3
  - More sensitivity to phase noise, timing and frequency offset
  - Greater complexity
  - Efficiency gains reduces by requirement for guard interval

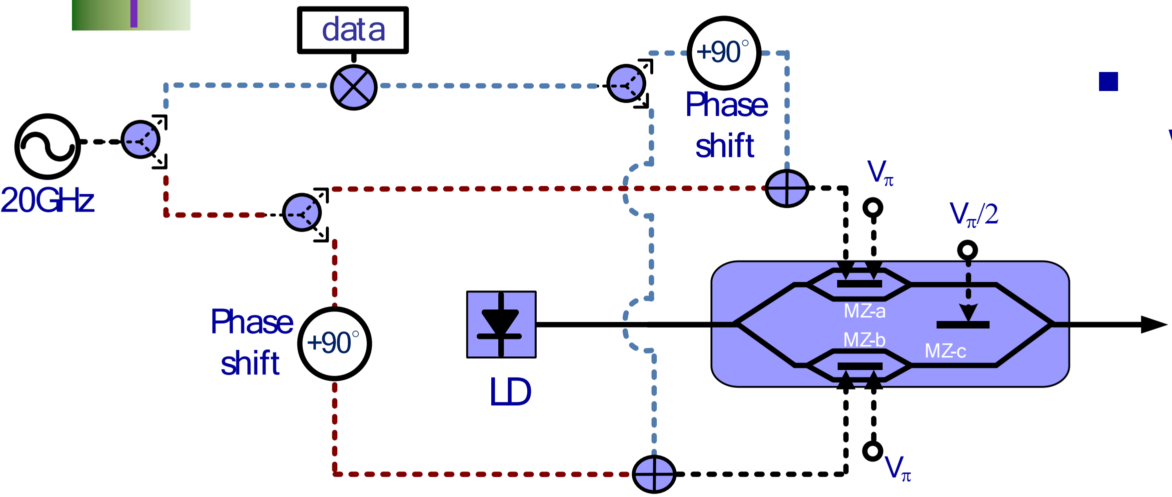
Optical OFDM

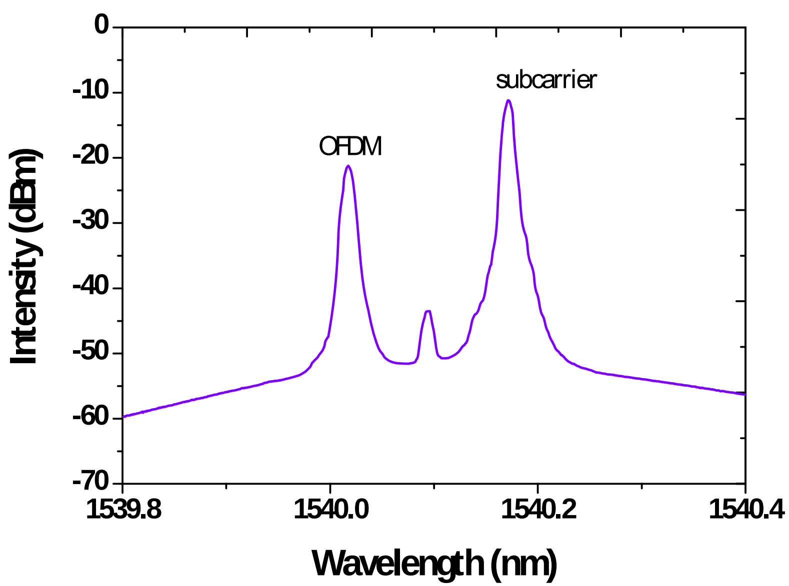
- Hybrid OFDM RoF system
  - no format conversion at base station
  - high spectra efficiency modulation format
  - Compared with square-law detection, OFDM can correct for **linear** (e.g. chromatic dispersion, PMD) and/or **nonlinear** (SPM) distortion⇨ the power of DSP
- Optical OFDM
  - Coherent OFDM (CO-OFDM): required **phase tracking** (OPLL) and **narrow line-width** local laser source (LO)
  - Remote heterodyne detection: simpler transmitter and receiver design



Nortel : 90 nm CMOS Rx-ASIC with 4x23Gs/s, 6 bits A/D, and 12 trillion operation per second.
DSP can correct the combined effects of 100 ps distributed PMD, fiber nonlinearity and chromatic dispersion of 3200 km of G.652 fiber.
(OFC 2008, tutorial NWC3, OFC2008, PDP 9 Optics express, 2008, Jan. pp. 873-879)

Remote Heterodyne OFDM RoF System





- Double sideband scheme with carrier suppression
  - OFDM at LSB and sinusoidal subcarrier at USB
  - Full OMI (optical modulation index) and no RF fading
  - Frequency doubling technique ⇨ low frequency electronic components for millimeter-wave service
  - High spectral efficiency: 64 QAM ⇨ 6 bit/(Hz·s)
  - DSP based impairments equalization

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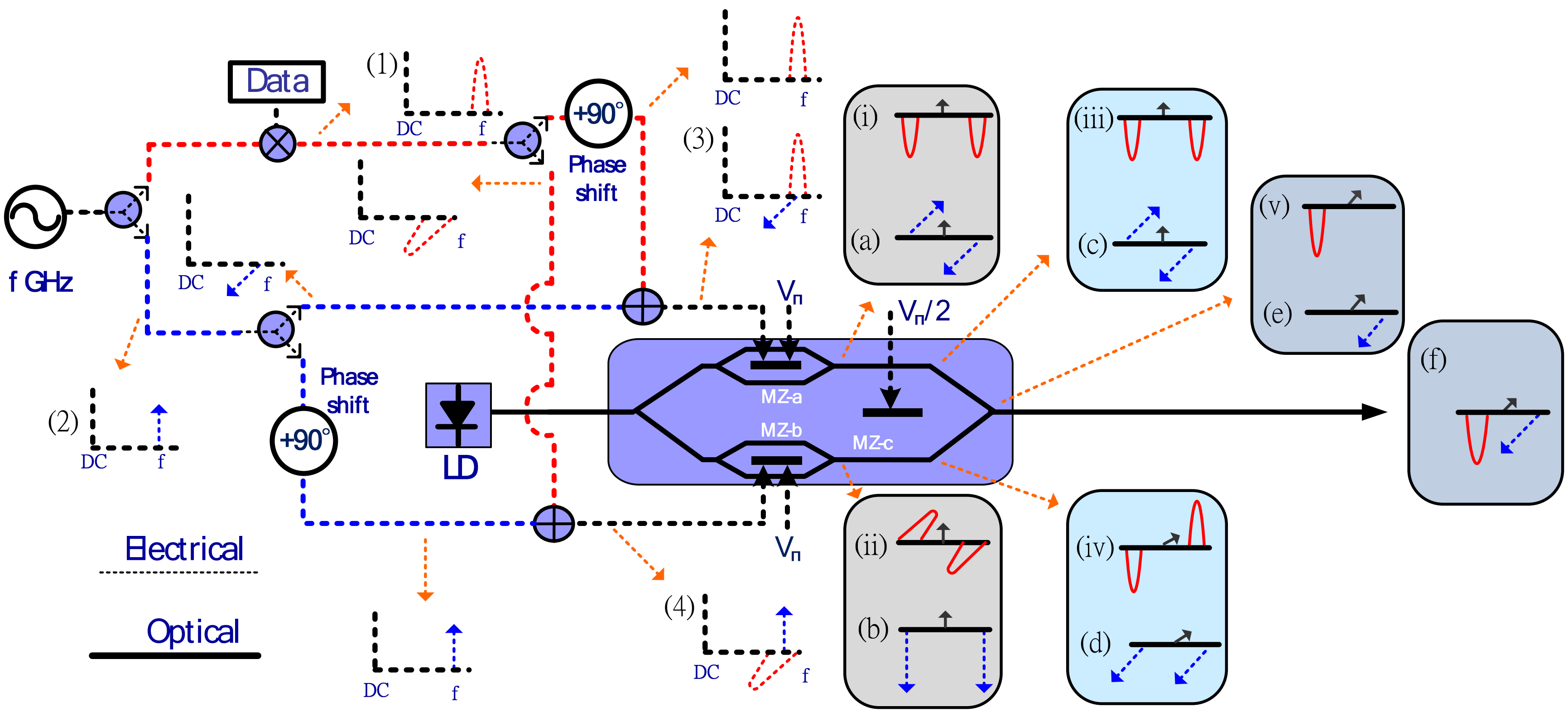
Concept of Remote Heterodyne OFDM System



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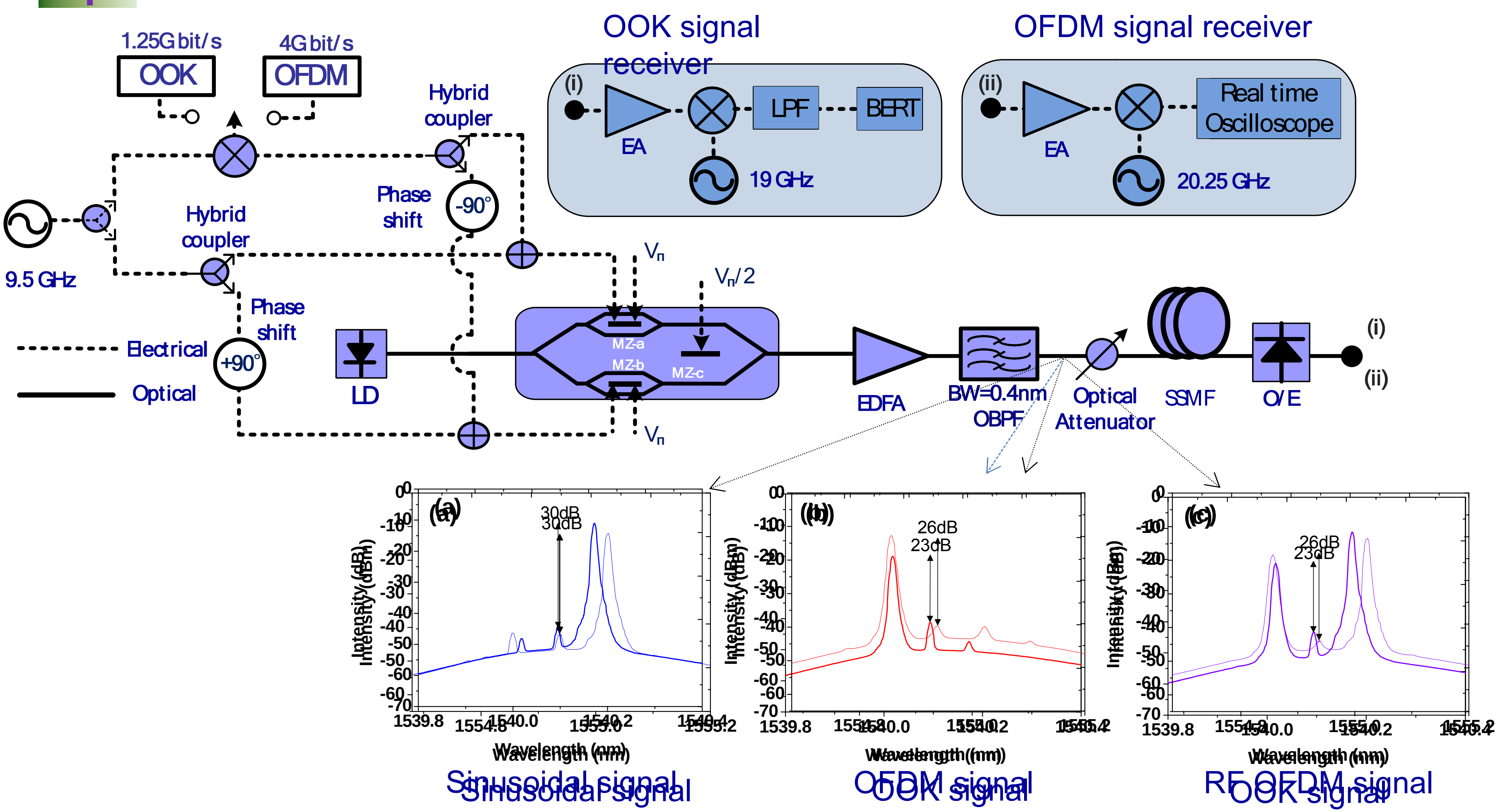
Experiment Setup



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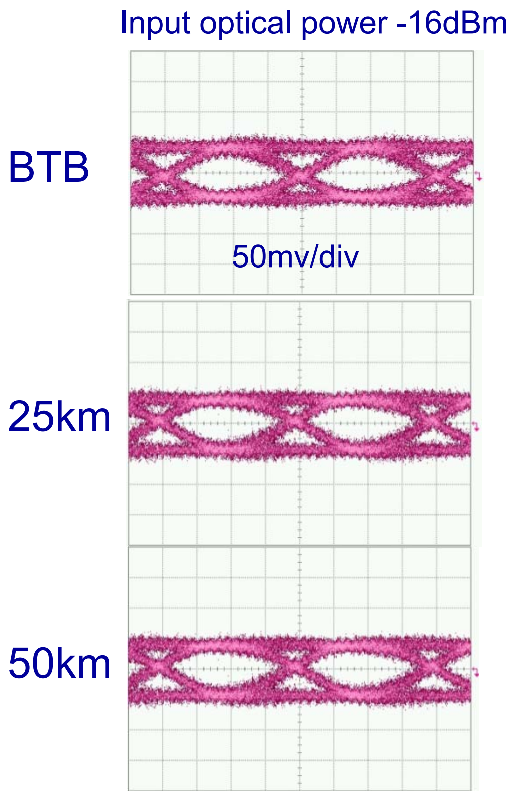
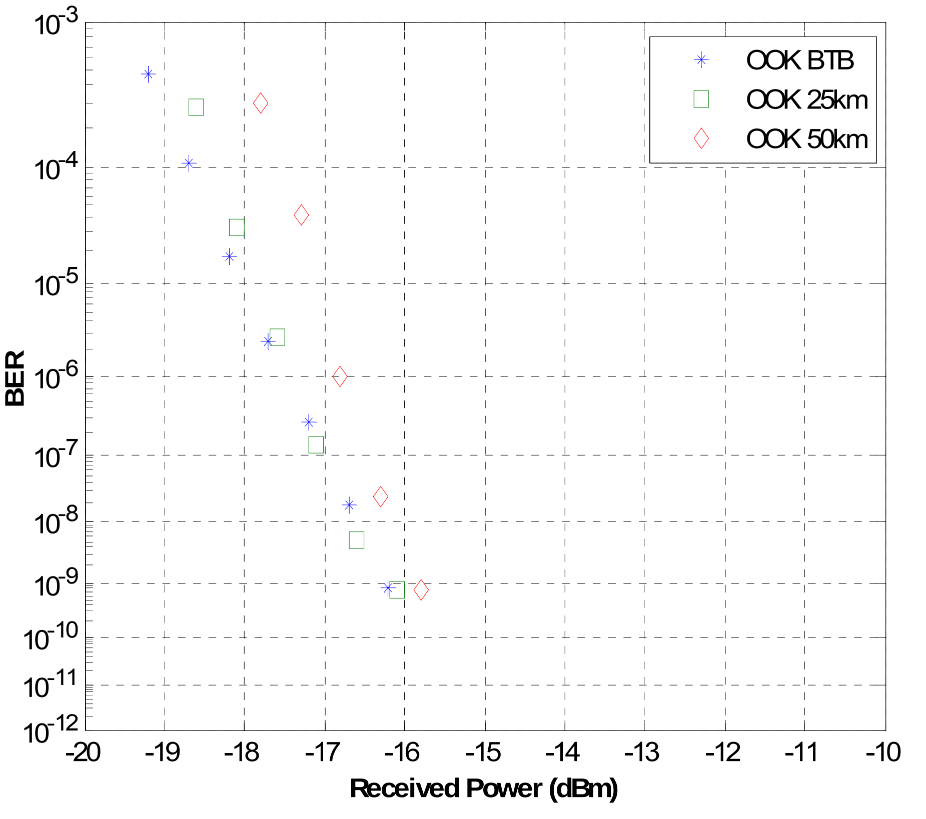
Experiment results: 1.25 Gb/s OOK Signal



Eye diagram of OOK signals.



BER curves of OOK signals.
The penalty was less than 0.4 dB.

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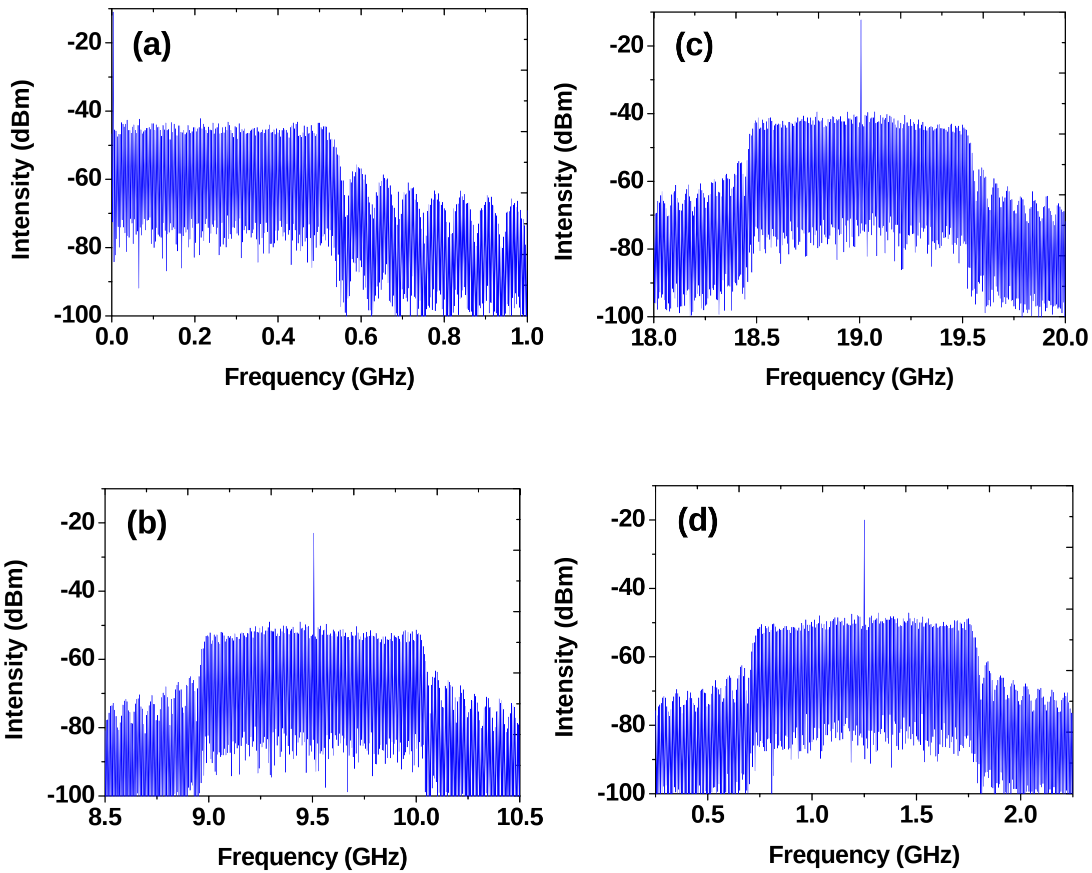
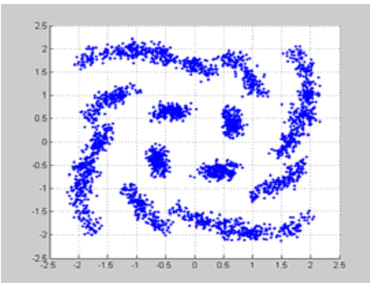
Experiment results: 16 QAM 4 Gb/s OFDM Signal

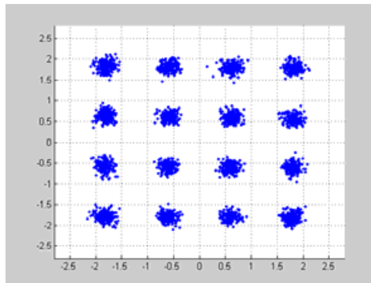


- After AWG, 8 carriers, each subcarrier is encoded with 62.5 MHz 16-QAM symbol-(a)
- After up-conversion , 16 subcarriers , bandwidth=1 GHz. (b)
- After PD , this signal can be directly utilized for wireless transmission. (c)
- OFDM signal is down-converted to 1.25 GHz. (d)

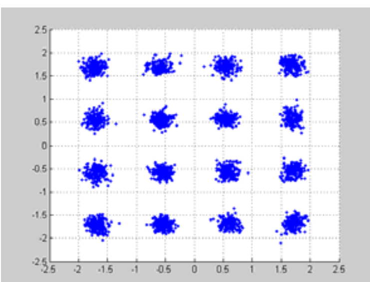
Constellation and BER of OOK and OFDM Signals



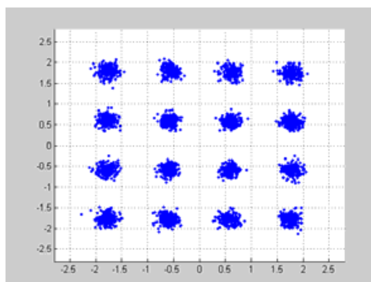
BTB w/o equalizer



BTB w/i equalizer

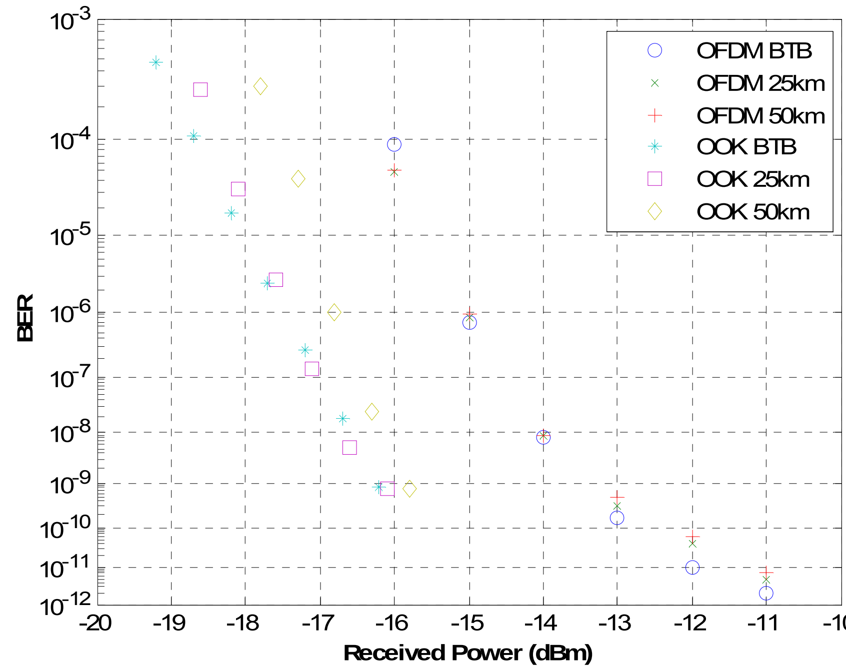


After 25km SMF.



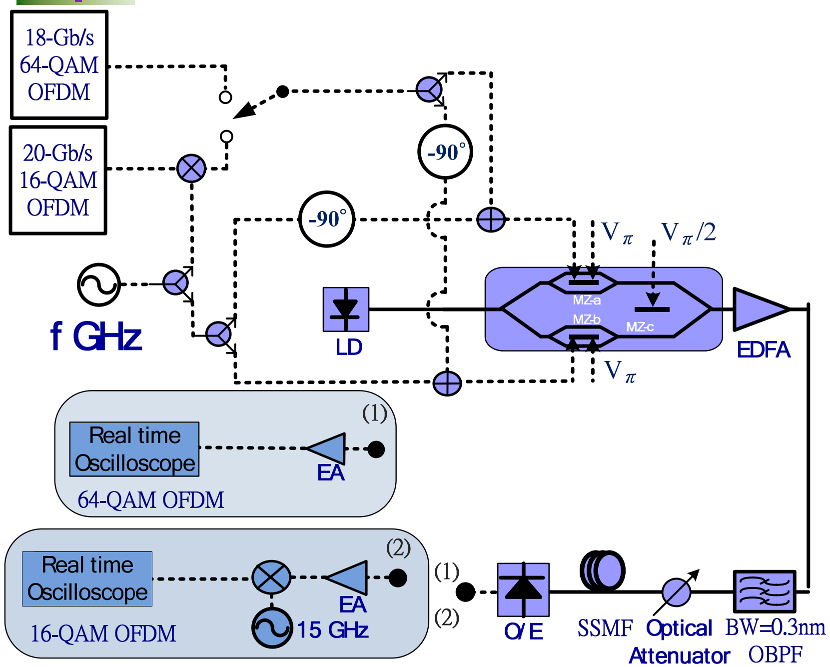
After 50km SMF.

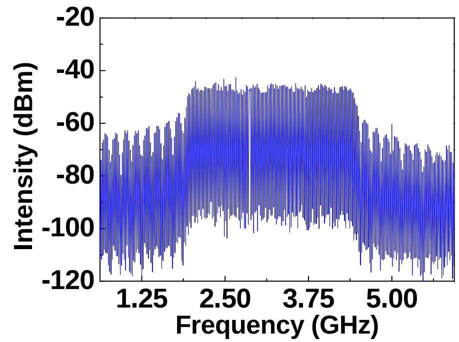
Off-line DSP program is employed to demodulate the OFDM signal



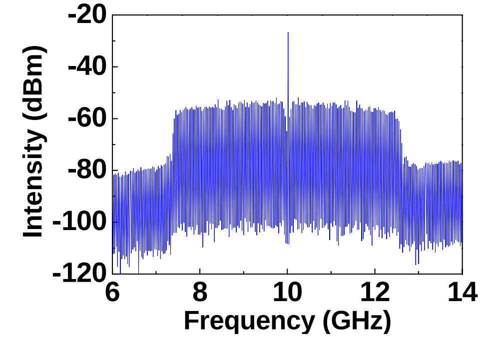
Benchmarked again OOK signal, OFDM has 4 times higher spectral efficiency with 2.5 dB penalty.

18 Gb/s 64-QAM and 20 Gb/s 16-QAM OFDM Signal

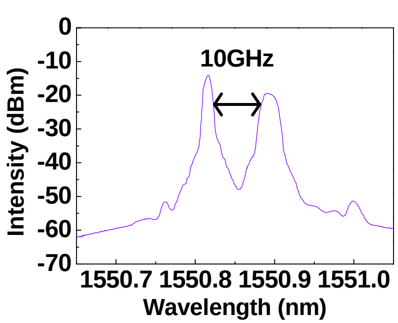




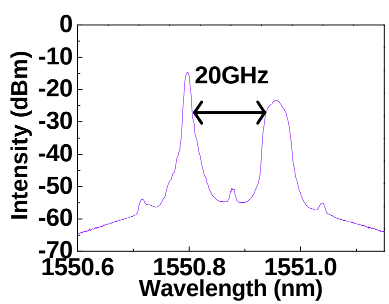
(c) 18 Gb/s 64 QAM (D: 3.22 GHz+ S: 6.782 GHz)



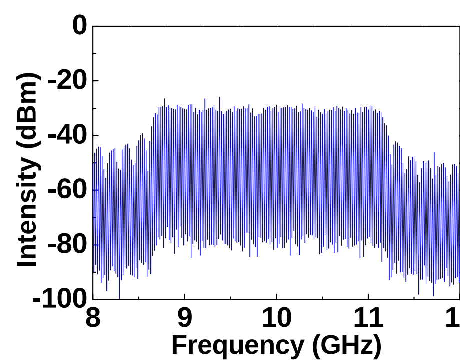
(d) 20 Gb/s 16 QAM



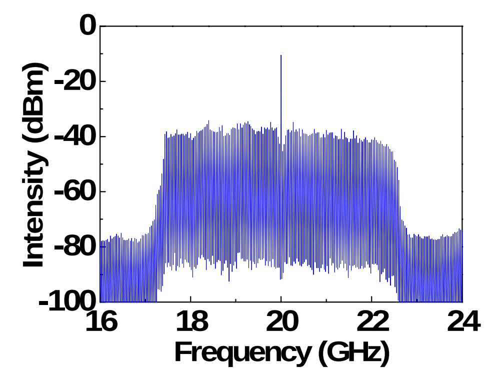
(a) 18 Gb/s 64 QAM



(b) 20 Gb/s 16

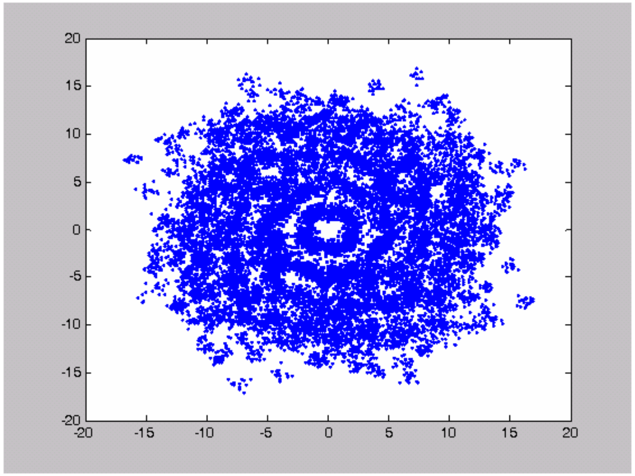


(e) PD: 18 Gb/s 64 QAM

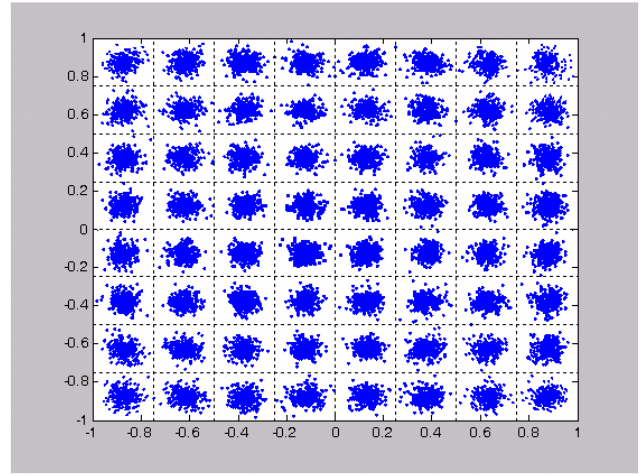


(f) PD: 20 Gb/s 16

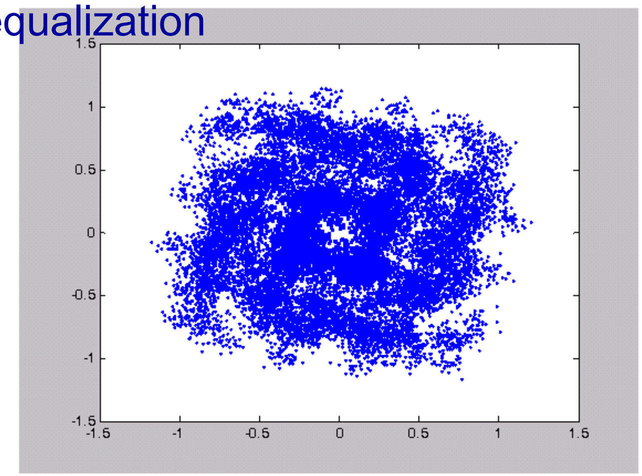
18 Gb/s 64-QAM and 20 Gb/s 16-QAM OFDM Signal



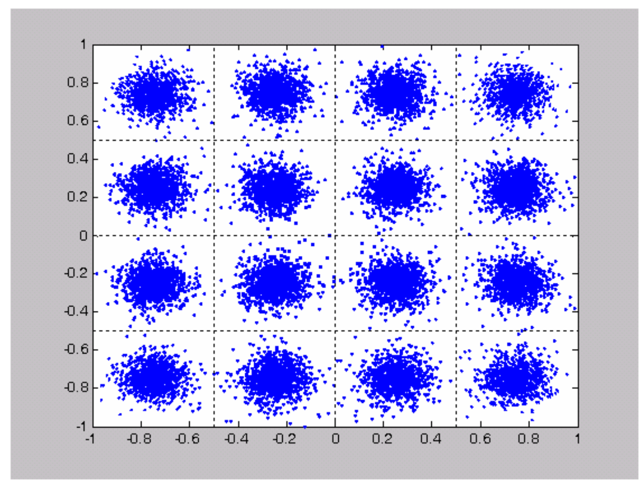
(a). 18 Gb/s 64-QAM before equalization



(b). 18 Gb/s 64-QAM after equalization

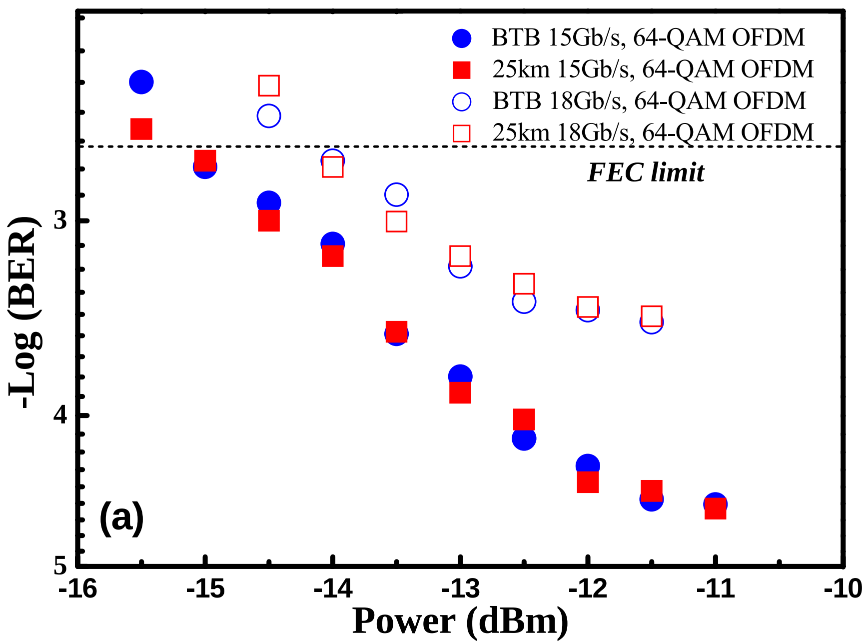


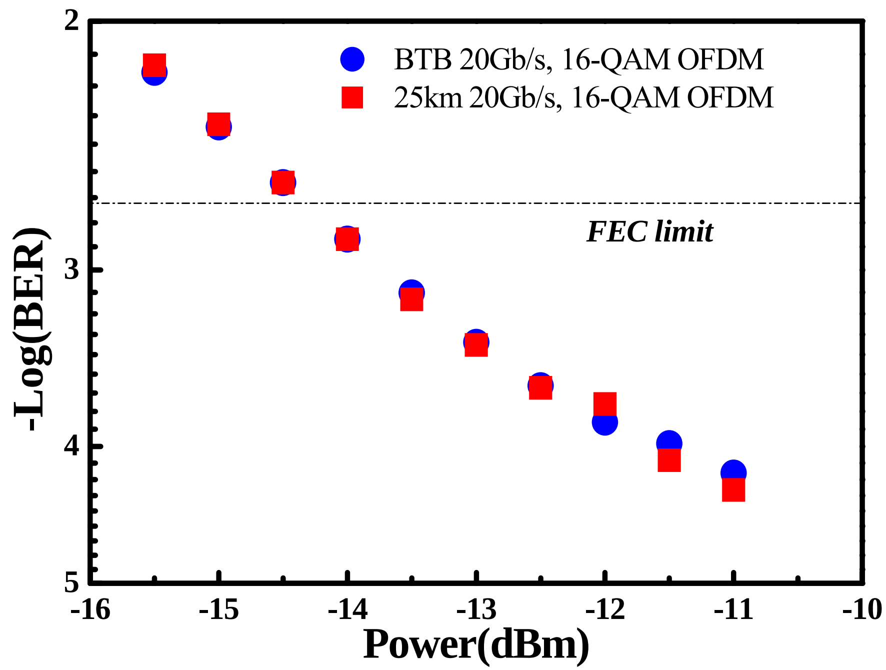
(c). 20 Gb/s 16-QAM before equalization



(d). 20 Gb/s 16-QAM after equalization

BER for 18 Gb/s 64-QAM and 20 Gb/s 16-QAM OFDM Signal





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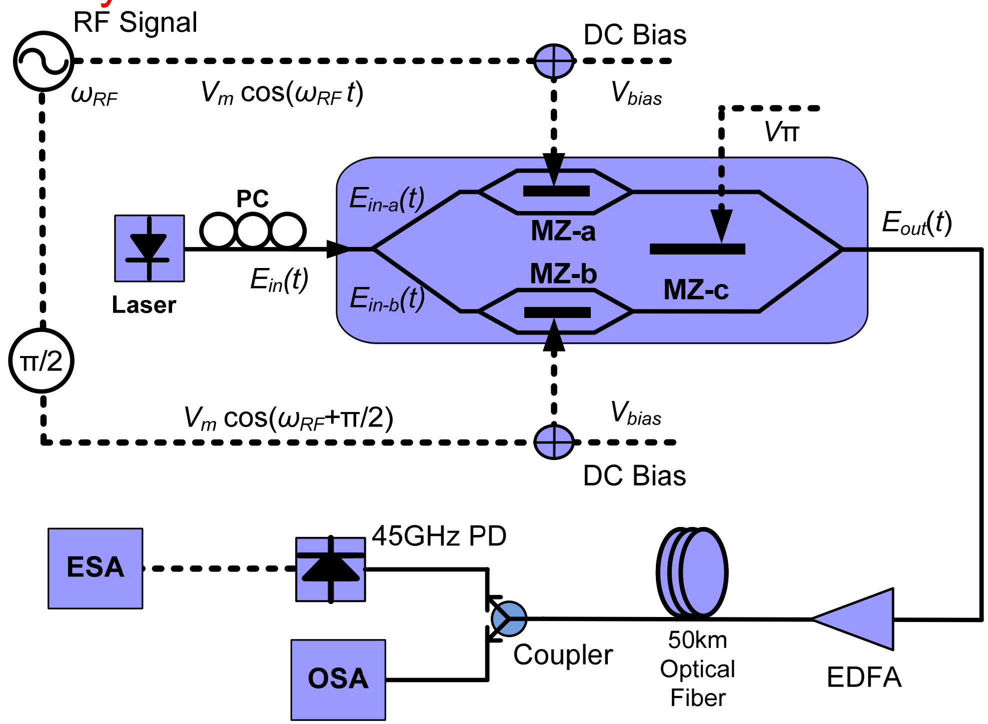
Application of Millimeter-wave Up-conversion: Wireless HD TV

- High Definition TV: uncompressed video and audio 3- 12 Gbps
  - Ex: 1920 Ｘ 1080 pixels ; RGB 3 colors per pixels ; 32 bit high color ; 60 Hz frame rate → 12 Gbps (video only)
- Wireless HD (WiHD) Interest Group:
  - Established by leading companies: (http://www.wirelesshd.org) 2006.10.31
  - Wireless digital interface to combine uncompressed high-definition video, multichannel audio data.
    - First generation 2 Gbps to 5 Gbps. Target 20 Gbps.
    - High-speed wireless, multi-gigabit technology in the unlicensed **60 GHz** band
    - Smart antenna technology to overcome line-of-sight constraints of **60 GHz** band

SiBEAM wireless beyond boundaries
TOSHIBA Leading Innovation
SONY sony style
SAMSUNG
LG Life's Good
Panasonic ideas for life
NEC Empowered by Innovation

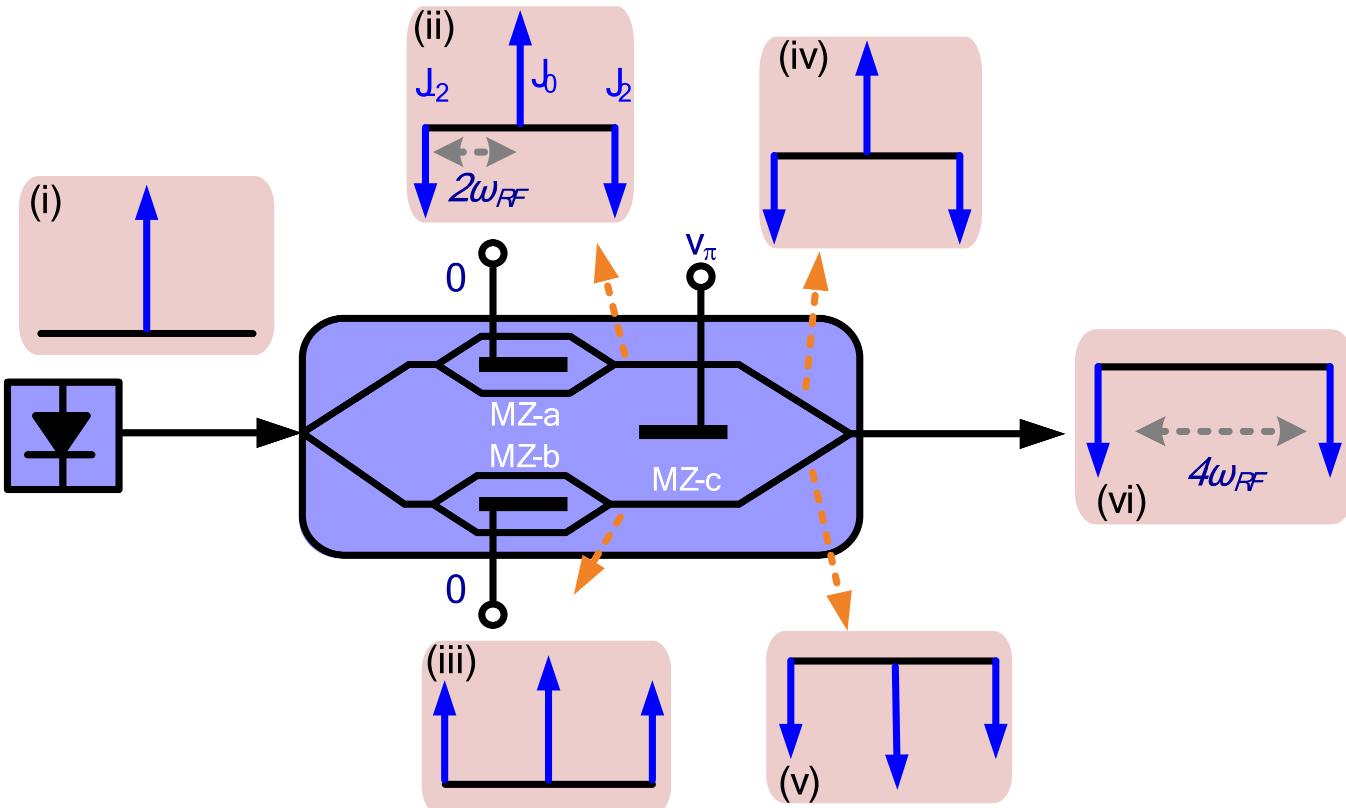
Generation of Millimeter-wave Signal using Frequency Quadrupling Technique

To generated Millimeter-wave signal beyond 40 GHz is still very expensive today!

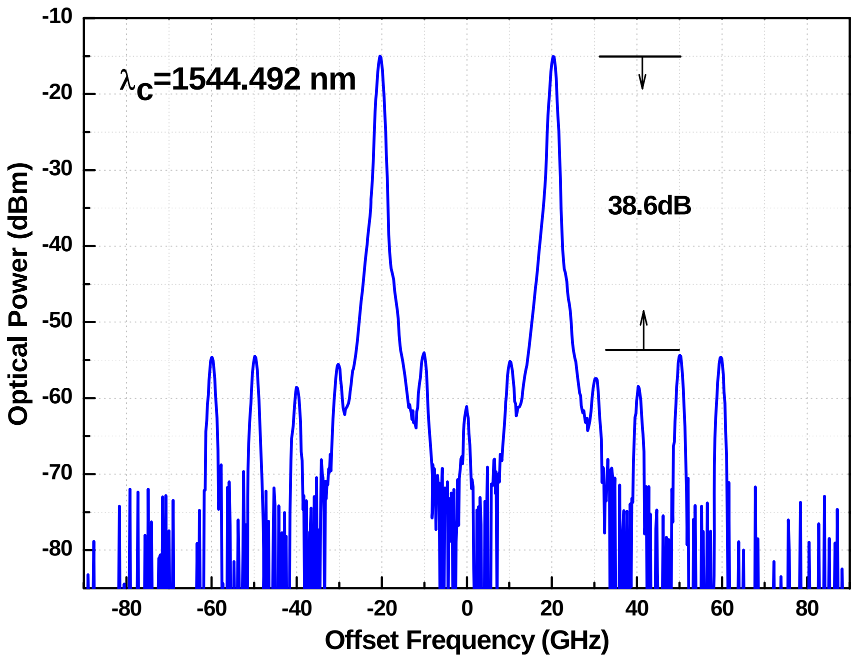


Optical up-conversion using a frequency multiplication technique for WDM RoF systems. (MZ: Mach -Zehnder modulator; EDFA: Erbium doped fiber amplifier; OSA: Optical Spectrum Analyzer; ESA: Electrical Spectrum Analyzer)

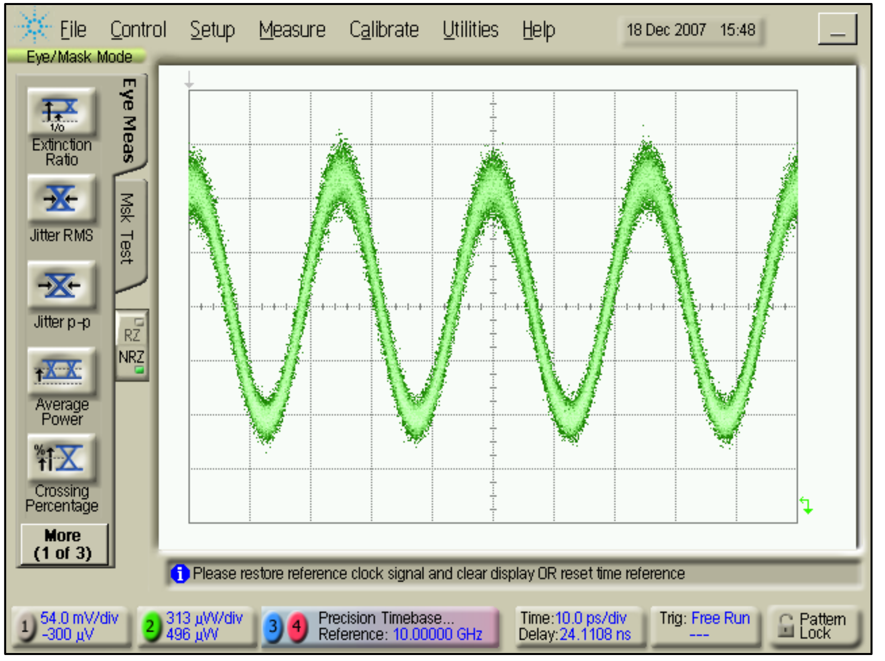
Principle of Frequency Quadrupling



Optical Spectrum and Waveform of 40 GHz Millimeter-wave Signal



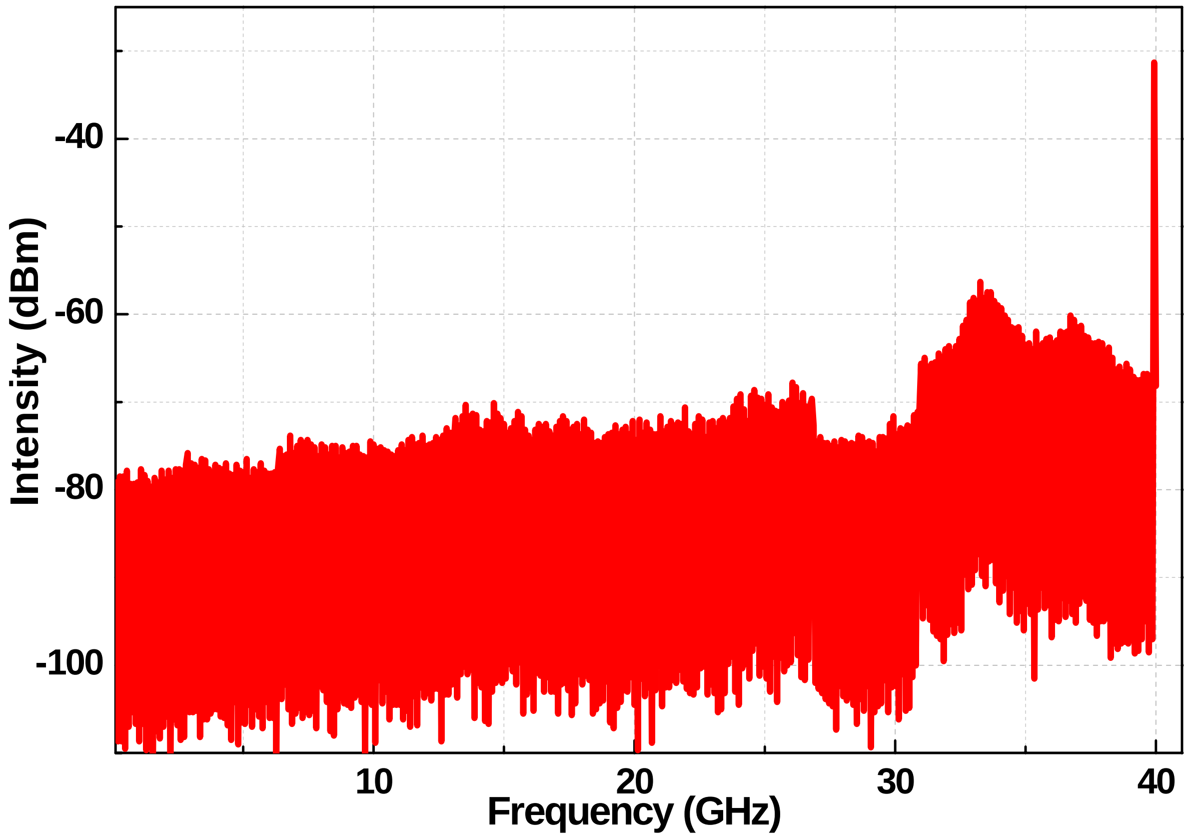
(a)



(b)

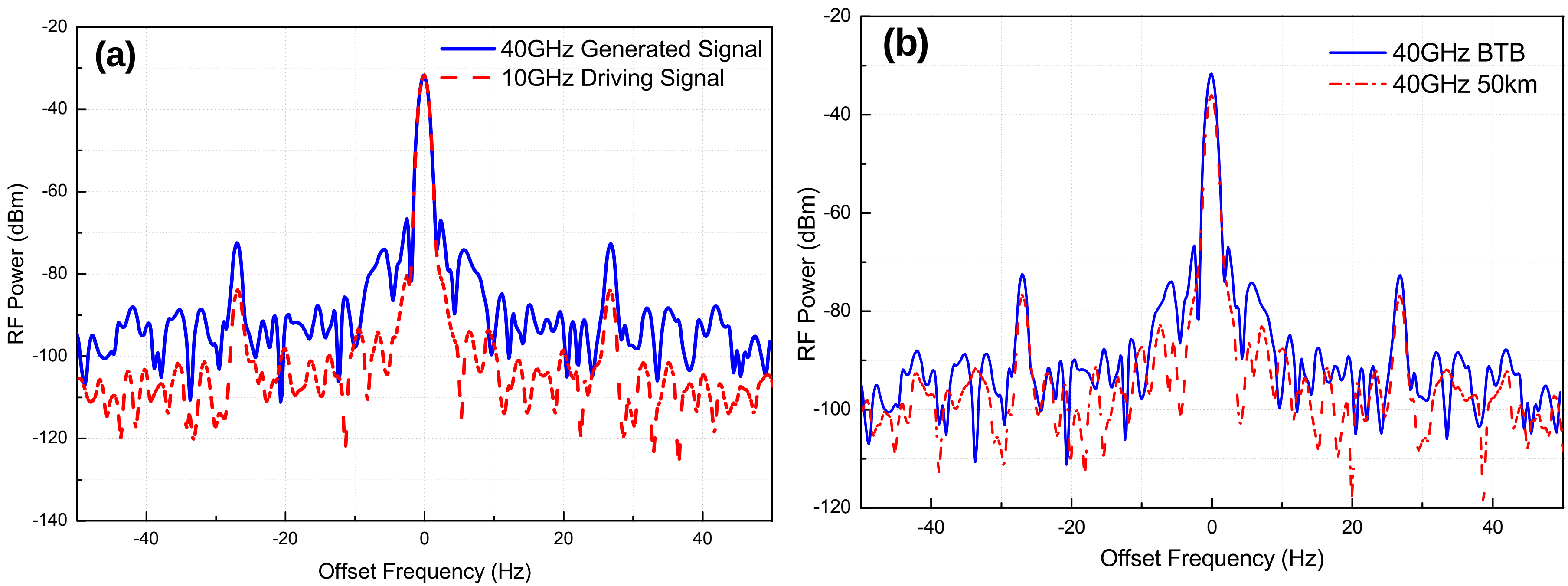
Experimental results of 40-GHz optical millimeter-wave signal with 10-GHz driving RF signal. (a) Optical spectrum. The resolution is 0.01-nm. (b) Optical waveform.

Electrical Spectrum of 40 GHz Millimeter-wave Signal



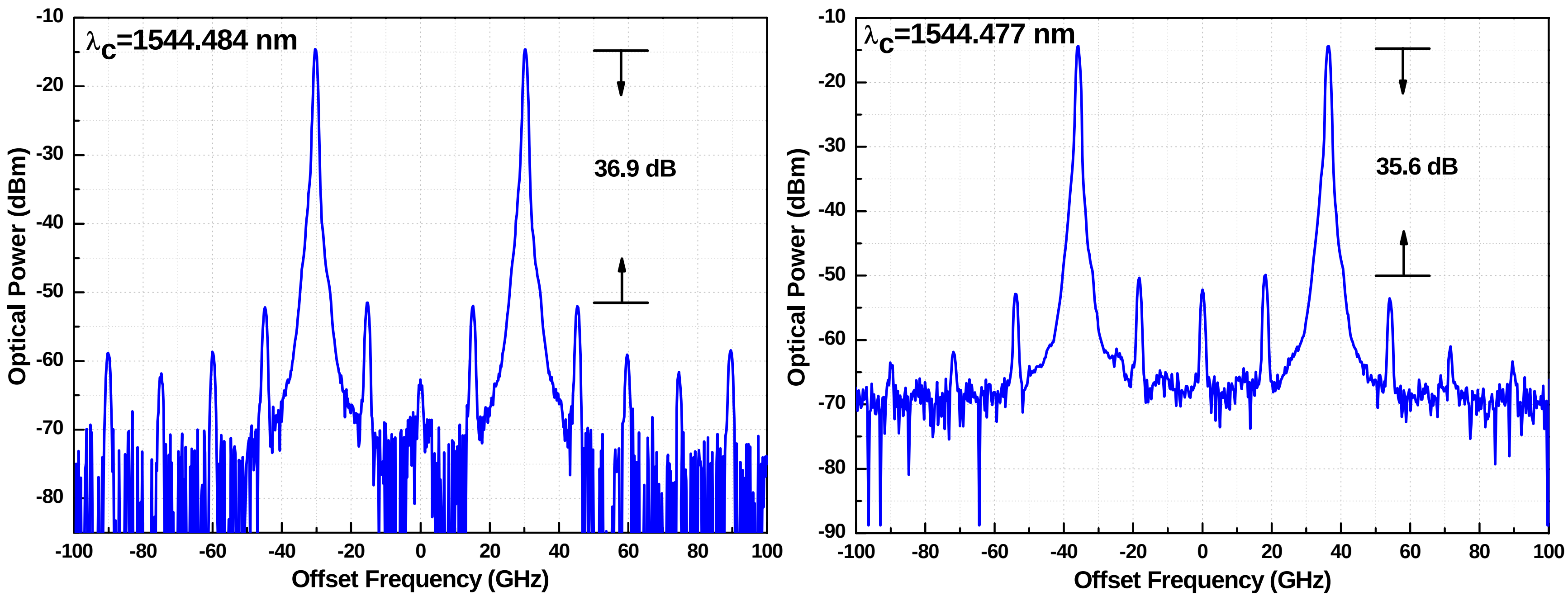
Electrical spectrum of the generated 40-GHz millimeter-wave signal with 10-GHz driving RF signal. (span 40 GHz; resolution bandwidth 30 kHz)

Linewidth of Generated Millimeter-wave Signal



Electrical spectrum of the generated 40-GHz millimeter-wave signal
(a) Comparison of generated 40-GHz signal and 10-GHz driving signal.
(b) Comparison of generated BTB and following 50 km SMF transmission 40-GHz signal.
(span 100 Hz; resolution bandwidth 1 Hz)

60 GHz and 72 GHz Millimeter-wave Generation

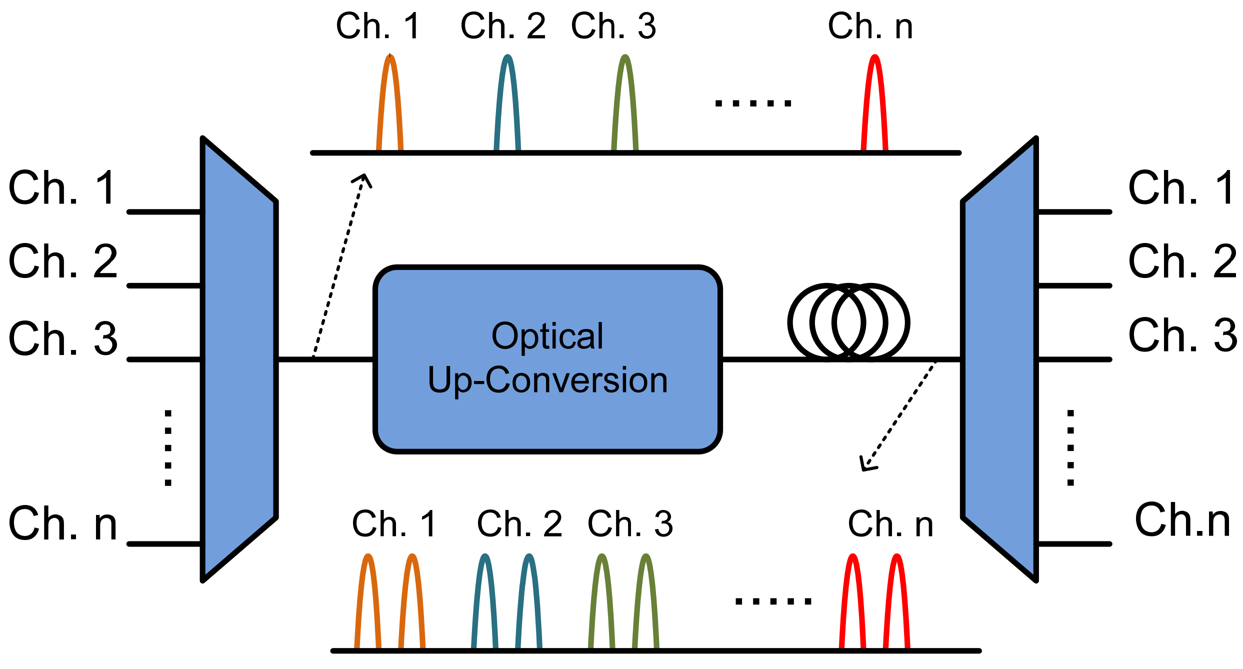


(a) (b)

Experimental results of optical millimeter-wave signal .
(a) 60 GHz. (b) 72 GHz.

Possible Applications: WDM Up-conversion

Since no optical filter is needed, the proposed scheme can be utilized in WDM RoF System and continuously tunable millimeter-wave signal generation systems.



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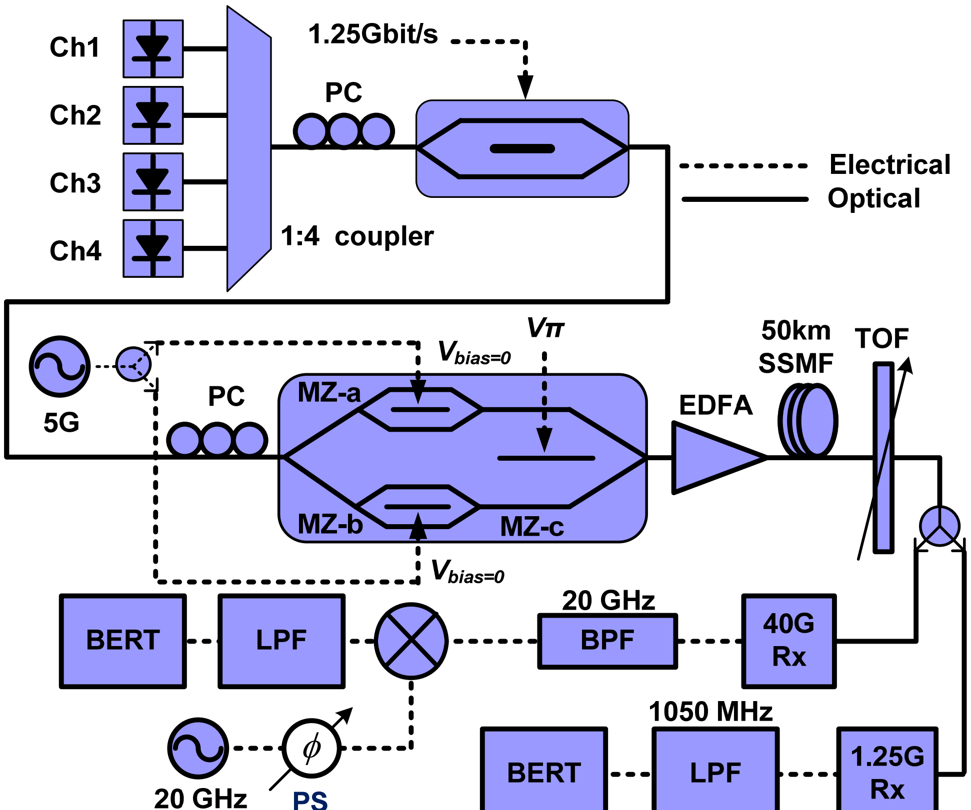
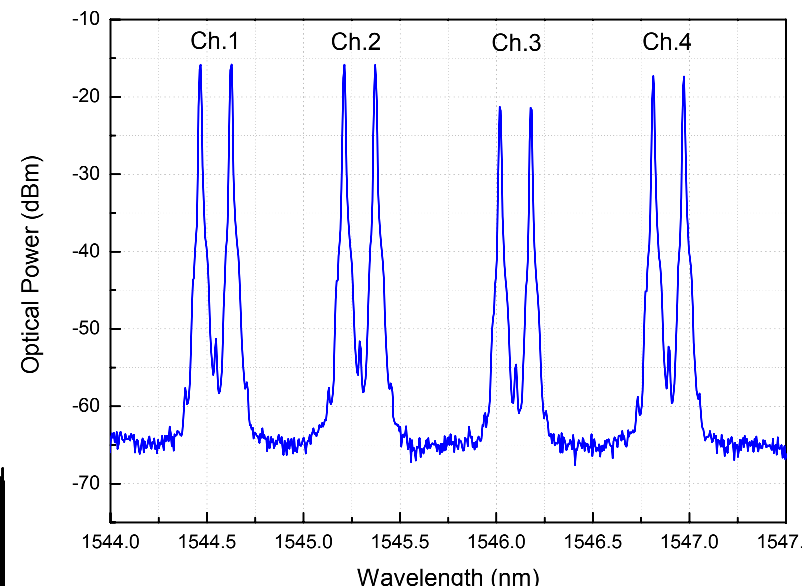
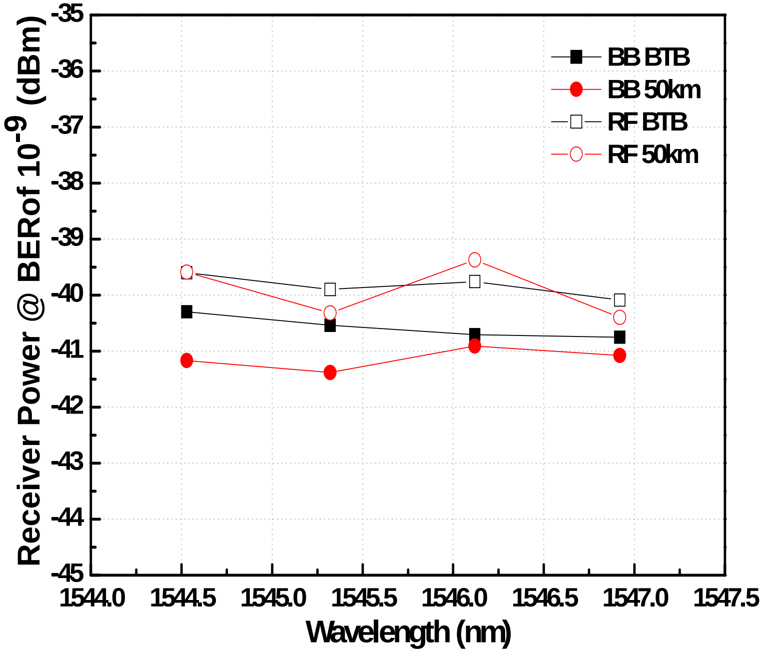
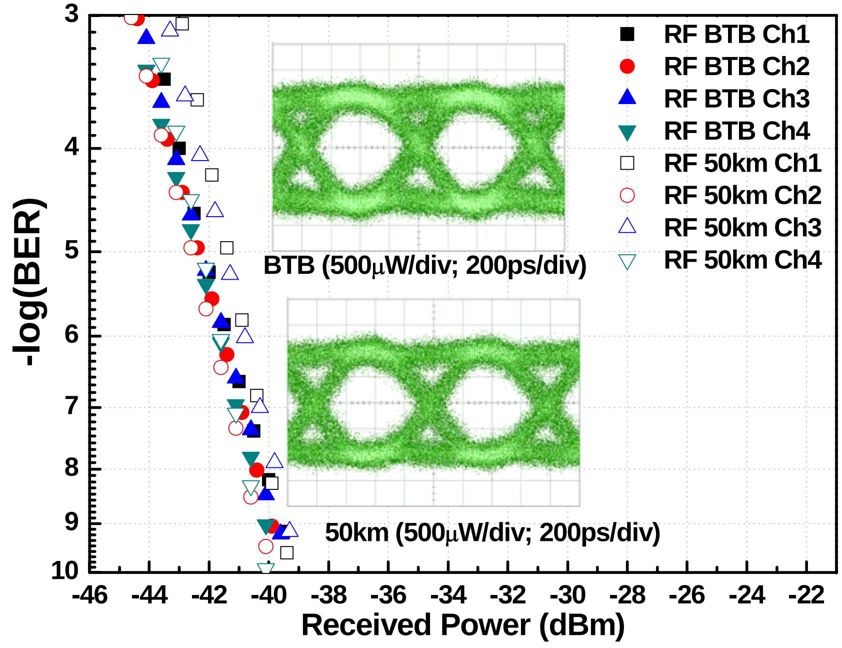
Architecture of 20 GHz WDM Up-Conversion System





BER of WDM Up-conversion System





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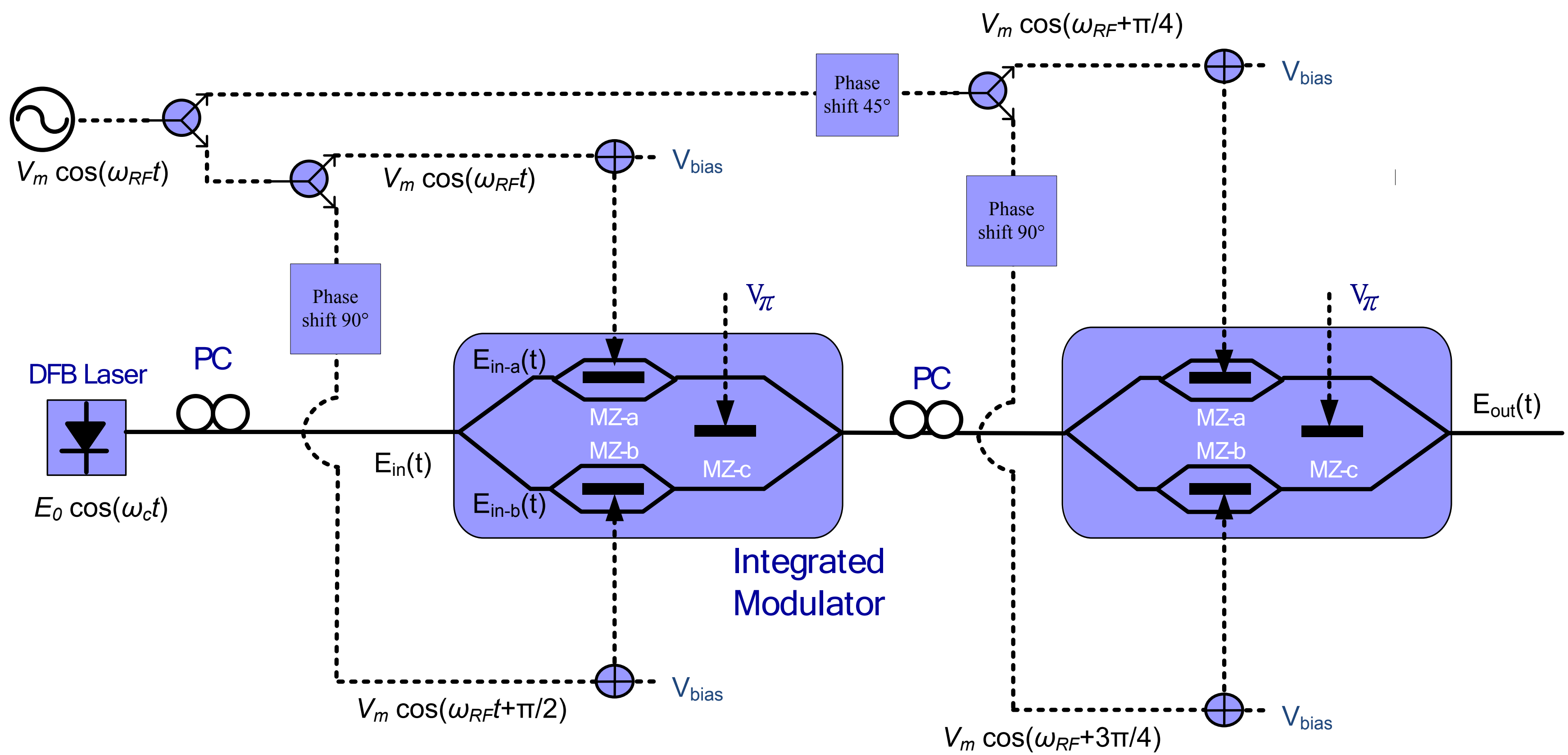
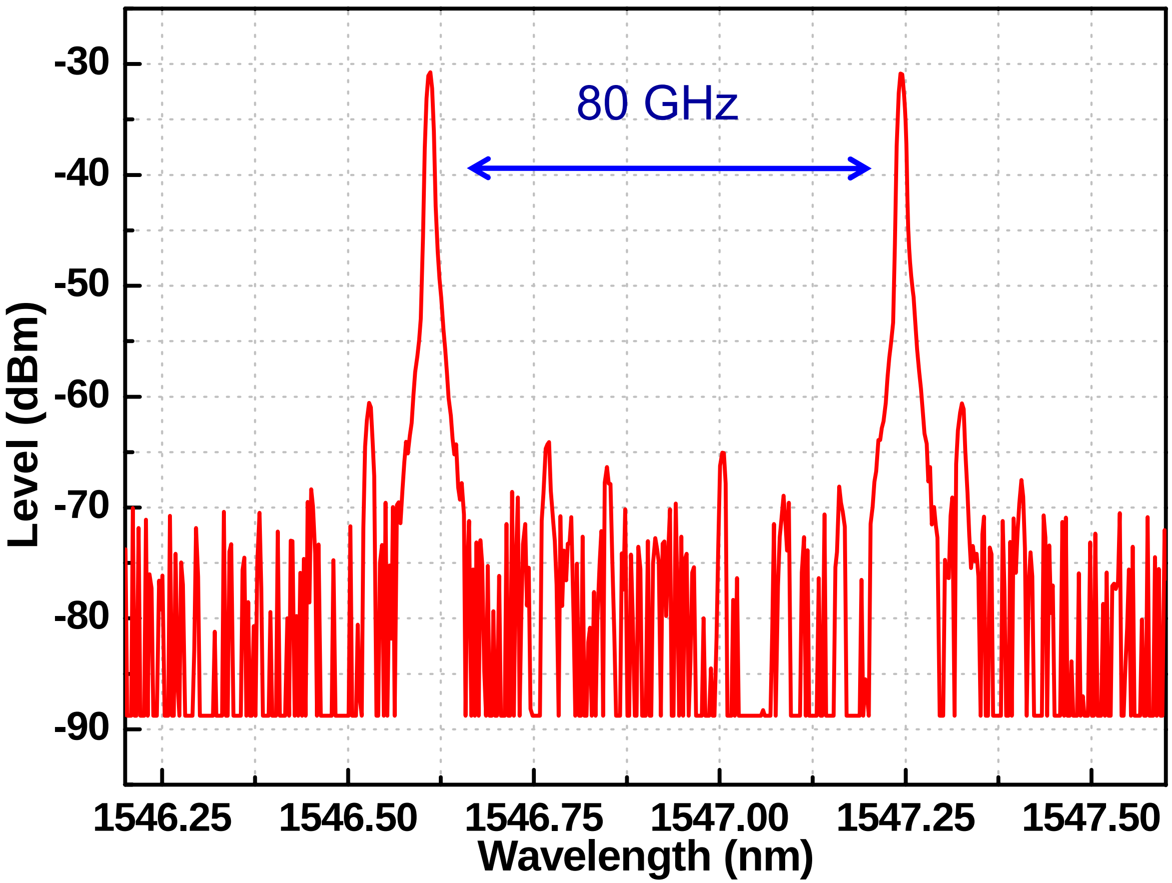
Frequency Octupling



80 GHz Frequency Octupling

The MZM has bandwidth of 20 GHz. This scheme is capable of generating 160 GHz millimeter wave signal. (due to limitation of driving amplifiers)

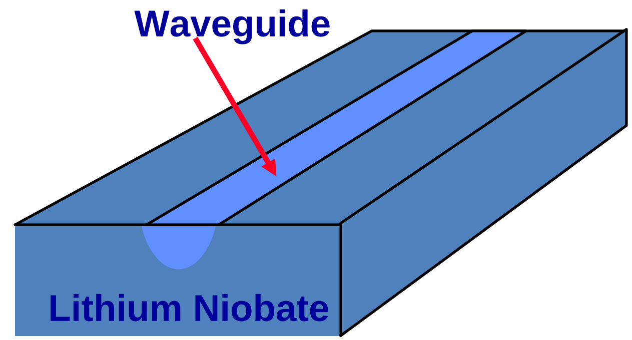


Conclusions

- Hybrid access network has the potential to fulfill the requirements for future broadband services
- Key technologies for hybrid access networks
  - Seamless integration of optical and wireless services: high spectral efficiency modulation format
  - Compared with **square-law** photo detection, **linear** detection scheme preserved phase information enabling DSP base equalization: dispersion, PMD, even nonlinear distortion
  - Cost-effective millimeter-wave up-conversion techniques: frequency quadrupling or frequency octupling for 60 GHz and beyond

Thanks you!

$LiNbO_3$ Modulator as Pure Phase Modulator (I)



$$E(t) = \mathrm{Re}\left\{E_0 e^{j(\omega_0 t + \Delta\Phi)}\right\} = E_0 \cos(\omega_0 t + \Delta\Phi(t))$$

$$= E_0 \left[\cos(\omega_0 t)\cos\Delta\Phi(t) - \sin(\omega_0 t)\sin\Delta\Phi(t)\right]$$

For sinusoidal input voltage $\Delta\Phi(t) = \beta \cos(\omega_m t)$

$$E(t) = E_0 \left[\cos(\omega_0 t)\cos(\beta \cos(\omega_m t)) - \sin(\omega_0 t)\sin(\beta \cos(\omega_m t))\right]$$

We need to solve $\cos(\beta \cos(\omega_m t))$ and $\sin(\beta \cos(\omega_m t))$

Fundamental of Bessel Function (I)

The generating function of Bessel function is

$$g(x,t) = e^{(x/2)(t - 1/t)} = \sum_{n=-\infty}^{\infty} J_n(x)\, t^n$$

If we take $t = e^{i\theta}$, we have

$$e^{ix\sin\theta} = \sum_{n=-\infty}^{\infty} J_n(x)\, e^{in\theta}$$

Using the identity $J_{-n}(x) = (-1)^n J_n(x)$, we have

$$J_1(x)e^{i\theta} + J_{-1}(x)e^{-i\theta} = J_1(x)\left(e^{i\theta} - e^{-i\theta}\right) = 2iJ_1(x)\sin\theta$$

$$J_2(x)e^{2i\theta} + J_{-2}(x)e^{-2i\theta} = J_2(x)\left(e^{2i\theta} + e^{-2i\theta}\right) = 2J_2(x)\cos 2\theta$$

$$e^{ix\sin\theta} = \sum_{n=-\infty}^{\infty} J_n(x)\, e^{in\theta}$$

$$= J_0(x) + 2\left[J_2(x)\cos 2\theta + J_4(x)\cos 4\theta + \cdots\right]$$

$$+ 2i\left[J_1(x)\sin\theta + J_3(x)\sin 3\theta + \cdots\right]$$

Fundamental of Bessel Function (II)

Therefore we will have

$$\begin{cases} \cos(x\sin\theta) = J_0(x) + 2\sum_{n=1}^{\infty} J_{2n}(x)\cos(2n\theta) \\ \sin(x\sin\theta) = 2\sum_{n=1}^{\infty} J_{2n-1}(x)\sin\left((2n-1)\theta\right) \end{cases}$$

$$\begin{cases} \cos(x\cos\theta) = \cos\left(x\sin\left(\frac{\pi}{2}+\theta\right)\right) = J_0(x) + 2\sum_{n=1}^{\infty} J_{2n}(x)\cos\left(2n\left(\frac{\pi}{2}+\theta\right)\right) = J_0(x) + 2\sum_{n=1}^{\infty}(-1)^n J_{2n}(x)\cos(2n\theta) \\ \sin(x\cos\theta) = \sin\left(x\sin\left(\frac{\pi}{2}+\theta\right)\right) = 2\sum_{n=1}^{\infty} J_{2n-1}(x)\sin\left(\left(\theta+\frac{\pi}{2}\right)(2n-1)\right) = 2\sum_{n=1}^{\infty}(-1)^{n+1} J_{2n-1}(x)\cos\left((2n-1)\theta\right) \end{cases}$$

(ref: Bessel function and their applications, by B. G. Korenev, p. 23)

LiNbO$_3$ Modulator as Pure Phase Modulator (II)

$$\cos(\beta\sin\theta) = J_0(\beta) + 2\sum_{k=1}^{\infty} J_{2k}(\beta)\cos(2k\theta) \qquad \cos(\beta\cos\theta) = J_0(\beta) + 2\sum_{k=1}^{\infty}(-1)^{k} J_{2k}(\beta)\cos(2k\theta)$$

$$\sin(\beta\sin\theta) = 2\sum_{k=1}^{\infty} J_{2k-1}(\beta)\sin[(2k-1)\theta] \qquad \sin(\beta\cos\theta) = 2\sum_{k=1}^{\infty}(-1)^{k} J_{2k-1}(\beta)\cos[(2k-1)\theta]$$

$$E(t) = E_0\left[\cos\omega_c t\cos(\beta\cos\omega_m t) - \sin\omega_c t\sin(\beta\cos\omega_m t)\right]$$

$$= E_0\left\{\cos\omega_c t\left[J_0(\beta) + 2\sum_{k=1}^{\infty}(-1)^{k} J_{2k}(\beta)\cos(2k\omega_m t)\right]\right.$$

$$\left. - \sin\omega_c t\left[2\sum_{k=1}^{\infty}(-1)^{k} J_{2k-1}(\beta)\cos[(2k-1)\omega_m t]\right]\right\}$$

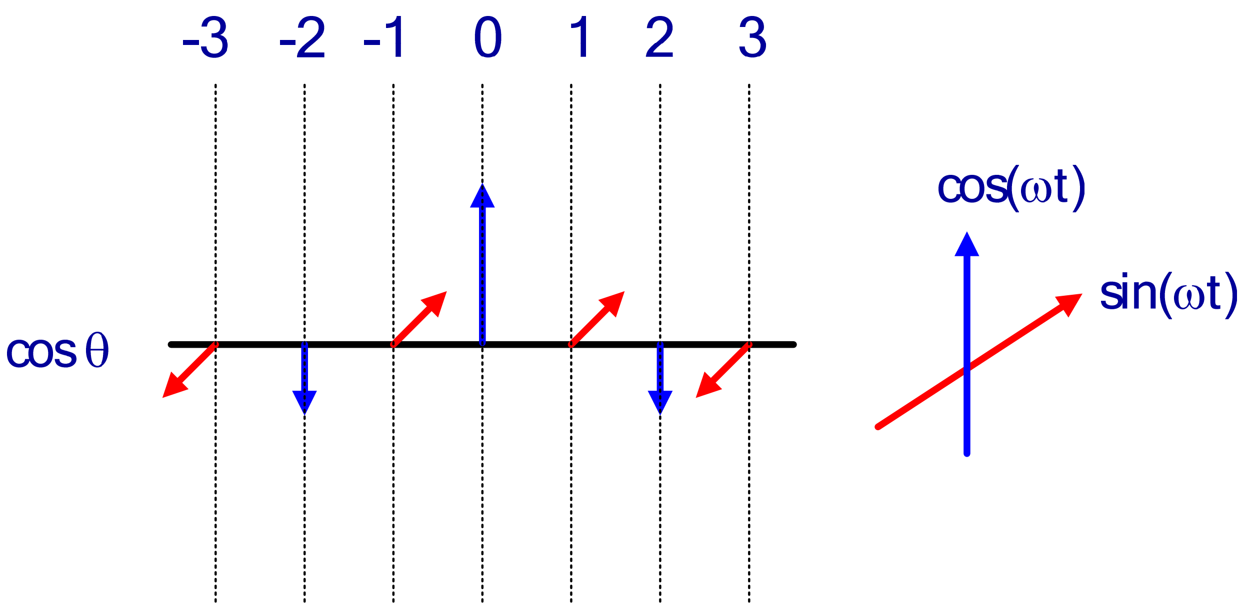
$$\cong \frac{1}{\sqrt{2}}E_0\left\{\cos\omega_c t\left[J_0(\beta) - 2J_2(\beta)\cos 2\omega_m t\right] + 2\sin\omega_c t\left[J_1(\beta)\cos\omega_m t - J_3(\beta)\cos 3\omega_m t\right]\right\}$$

$$= \frac{1}{\sqrt{2}}E_0\left\{J_0(\beta)\cos\omega_c t - J_2(\beta)\cos(\omega_c \pm 2\omega_m)t\right.$$

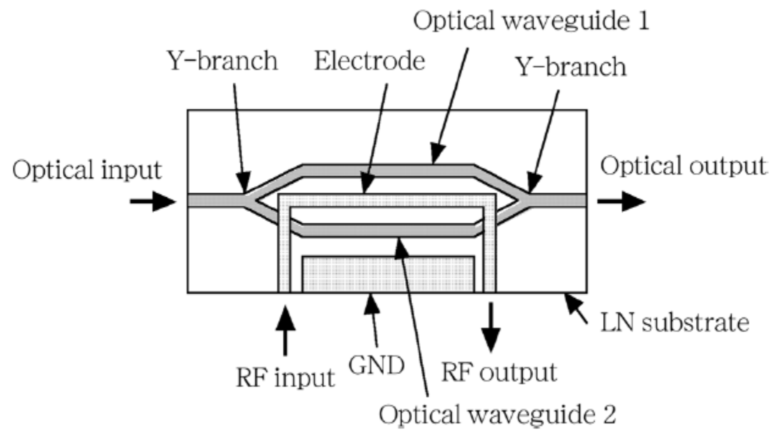
$$\left. + J_1(\beta)\sin(\omega_c \pm \omega_m)t - J_3(\beta)\sin(\omega_c \pm 3\omega_m)t\right\}$$

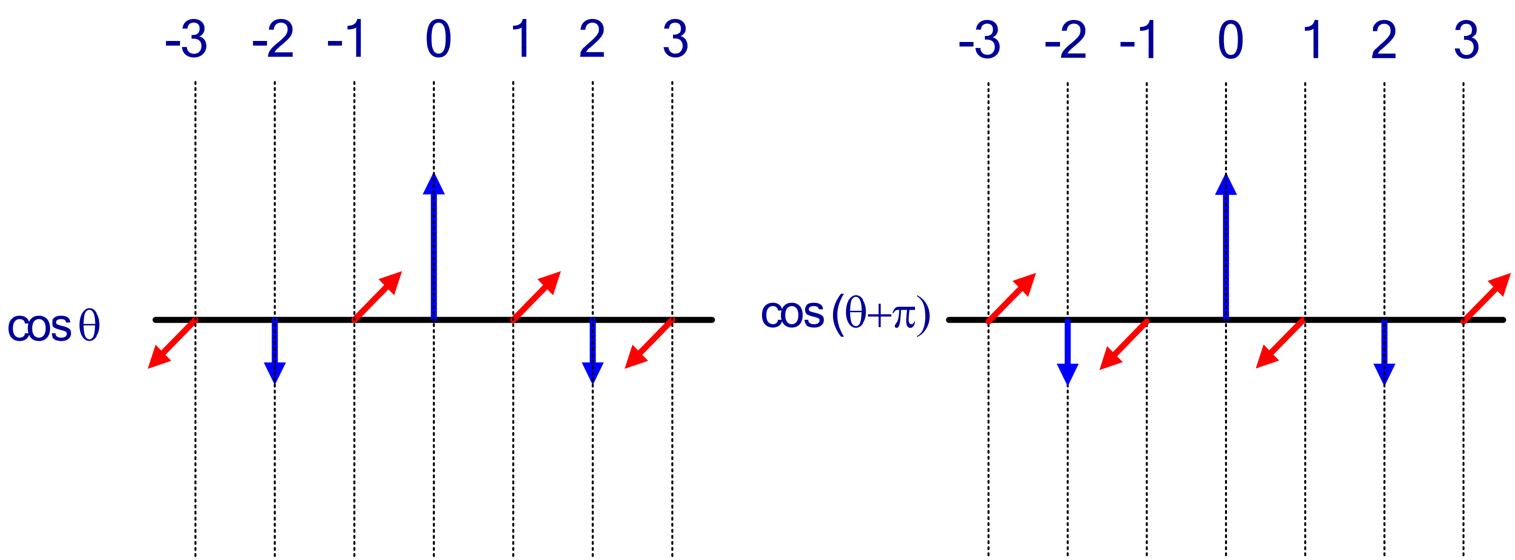
$LiNbO_3$ Modulator as Pure Phase Modulator (III)

$$E(t)=\frac{1}{\sqrt{2}}E_0\left[J_0(\beta)\cos(\omega_0 t)-J_2(\beta)\cos\left((\omega_0+2\omega_m)t\right)-J_2(\beta)\cos\left((\omega_0-2\omega_m)t\right)\right.$$
$$+J_1(\beta)\sin\left((\omega_0+\omega_m)t\right)+J_1(\beta)\sin\left((\omega_0-\omega_m)t\right)-J_3(\beta)\sin\left((\omega_0+3\omega_m)t\right)$$
$$\left.-J_3(\beta)\sin\left((\omega_0-3\omega_m)t\right)\right]$$

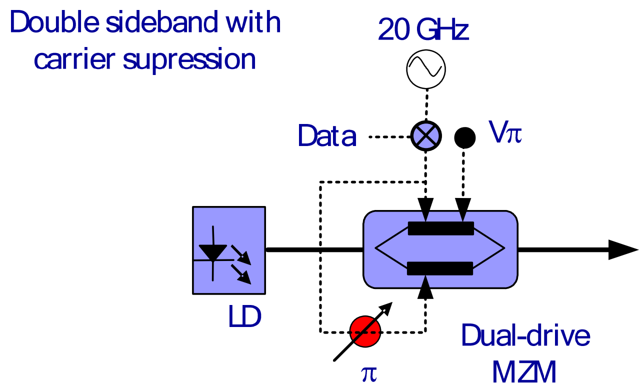


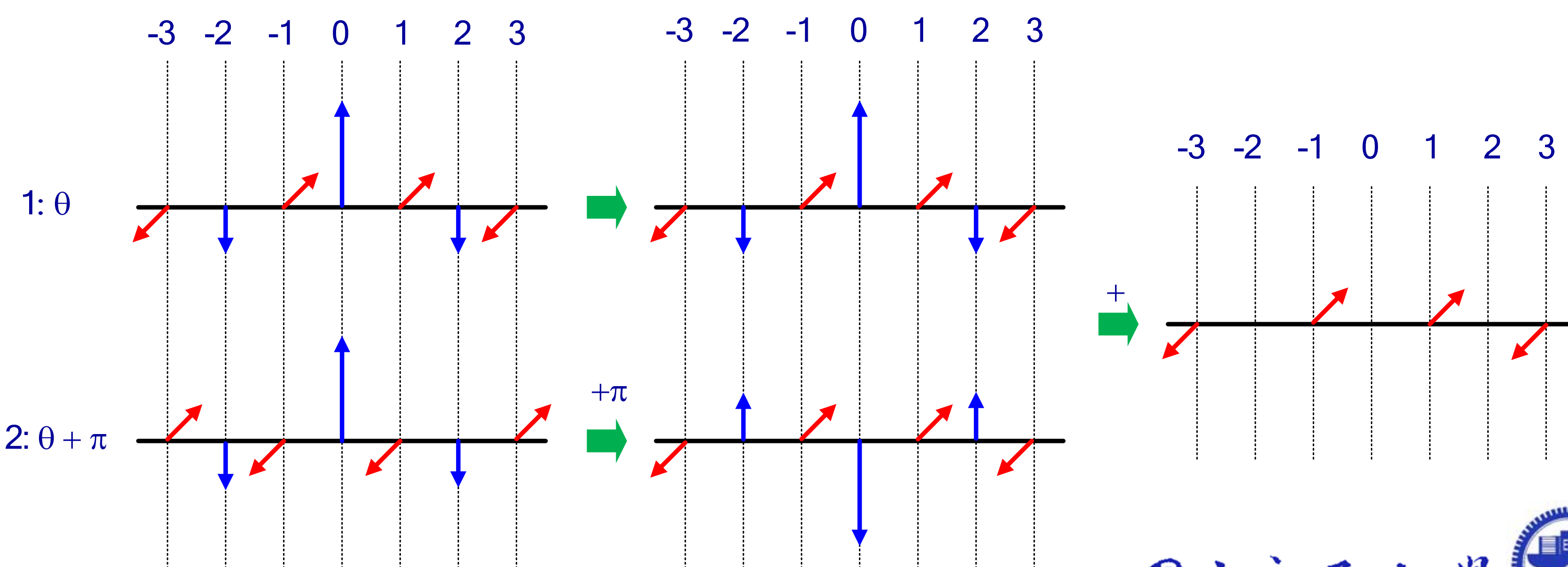
Single Drive Mach-Zehnder Modulator



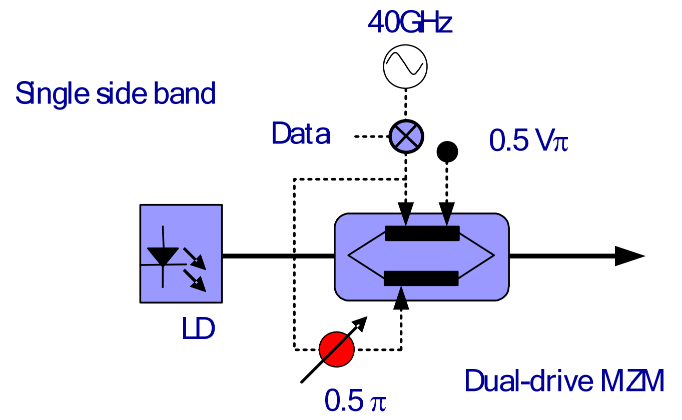


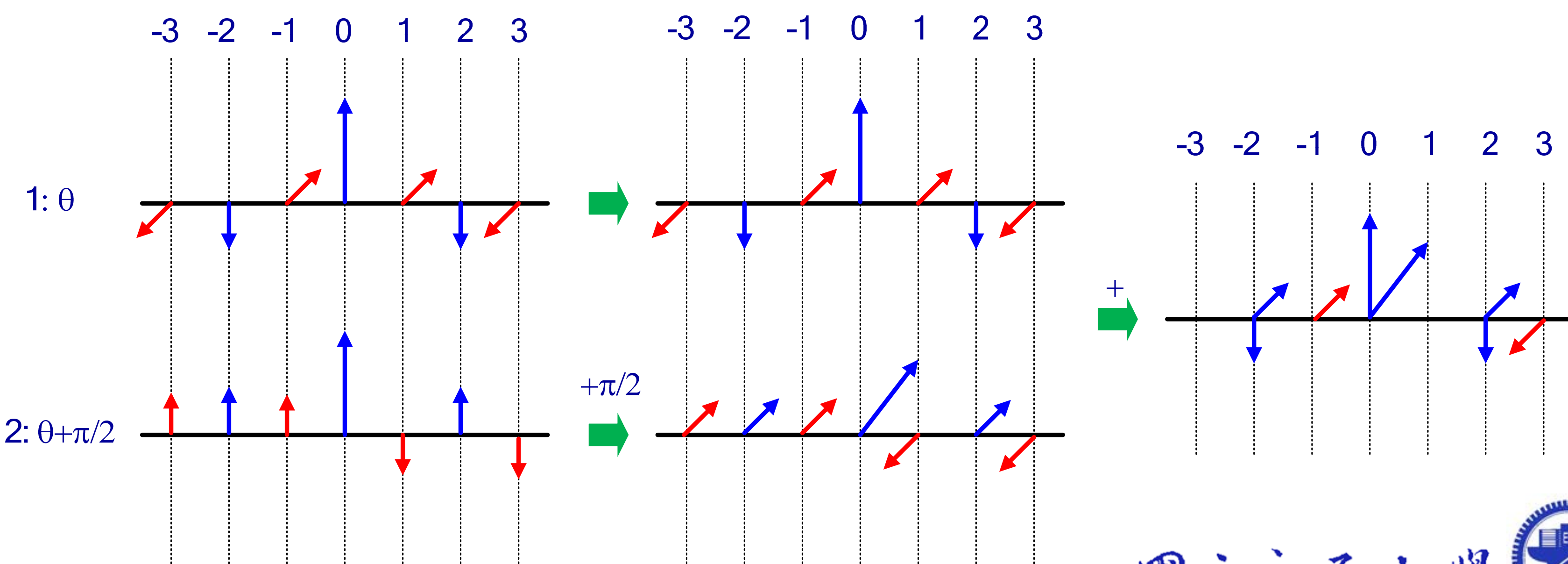
Double Sideband with Carrier Suppression





Single sideband using dual drive MZM





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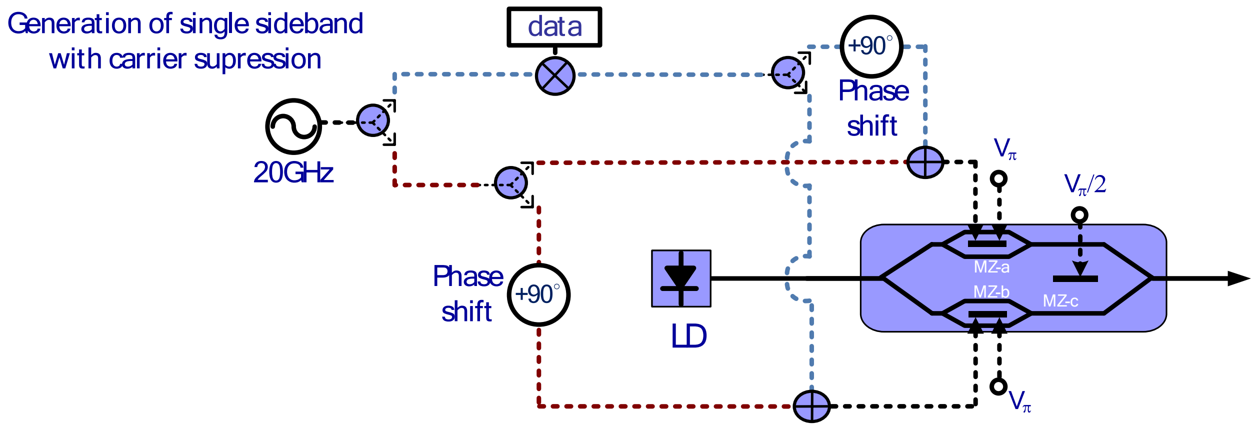
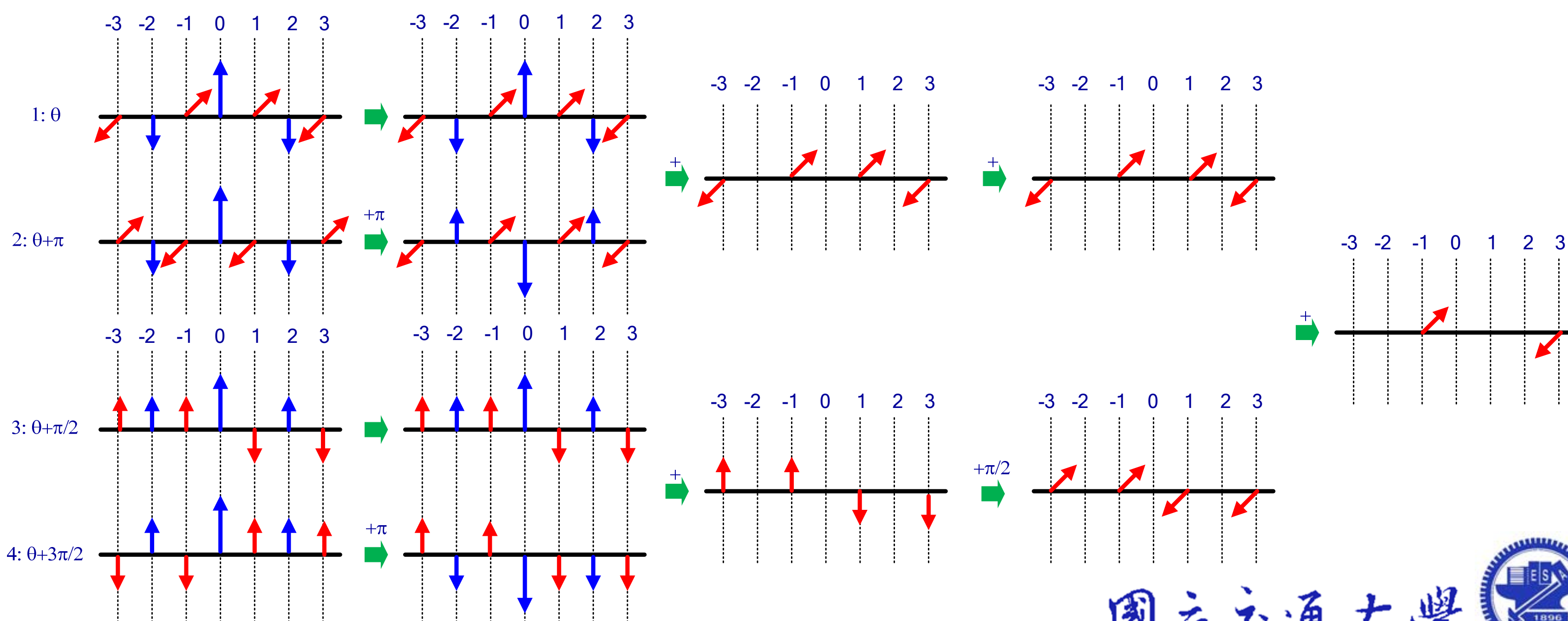
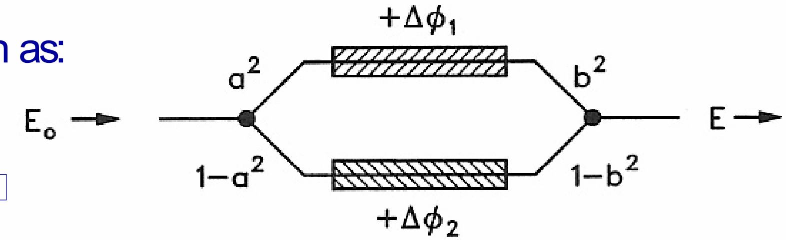
Single sideband with carrier suppression





Case I: MZM as a Pure Phase Modulator

For a typical MZM, the e-field and power can be written as:



$$E(t) = E_0 e^{j\omega_0 t} \cdot \left[a \cdot b \cdot e^{j\Delta\Phi_1} + \sqrt{1-a^2} \cdot \sqrt{1-b^2} \cdot e^{j\Delta\Phi_2} \right]$$

For perfect splitting ratio: $a = b = \frac{1}{\sqrt{2}}$

$$E(t) = \frac{1}{2} E_0 \left[e^{j\Delta\Phi_1} + e^{j\Delta\Phi_2} \right] e^{j\omega_0 t} = \frac{1}{2} E_0 e^{j\frac{\Delta\Phi_1+\Delta\Phi_2}{2}} \left[e^{j\frac{\Delta\Phi_1-\Delta\Phi_2}{2}} + e^{-j\frac{\Delta\Phi_1-\Delta\Phi_2}{2}} \right] e^{j\omega_0 t}$$

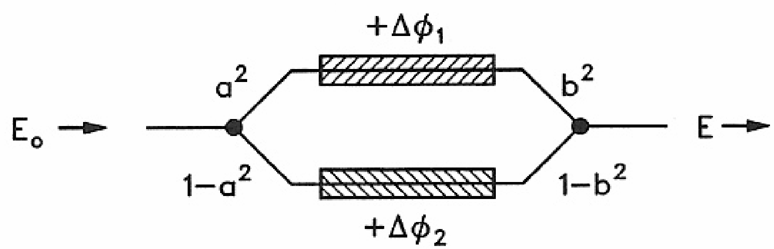
$$= E_0 e^{j\omega_0 t} \cdot \cos\left[\frac{\pi}{2V_\pi} (V_1 - V_2) \right] e^{j\frac{\pi}{2V_\pi}(V_1+V_2)}$$

Case I: if $V_1 = V_2 = V$, we have pure phase modulator

$$E(t) = \mathrm{Re}\left\{ E_0 e^{j\omega_0 t} \cdot e^{j\frac{\pi V(t)}{V_\pi}} \right\} = E_0 \cos\left[\omega_0 t + \frac{\pi}{V_\pi} V(t) \right]$$

$$= E_0 \left[\cos \omega_0 t \cos\left(\frac{\pi}{V_\pi} V(t)\right) - \sin \omega_0 t \sin\left(\frac{\pi}{V_\pi} V(t)\right) \right]$$

Case II: MZM as a Pure Intensity Modulator

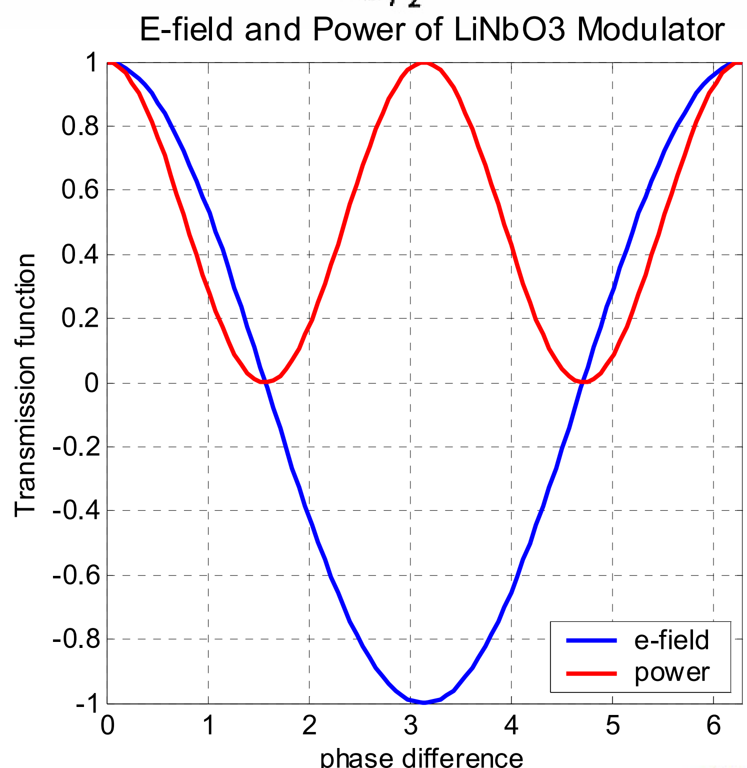


Case II: if $\square_1 = -\square_2 = \square$, we have pure intensity modulator

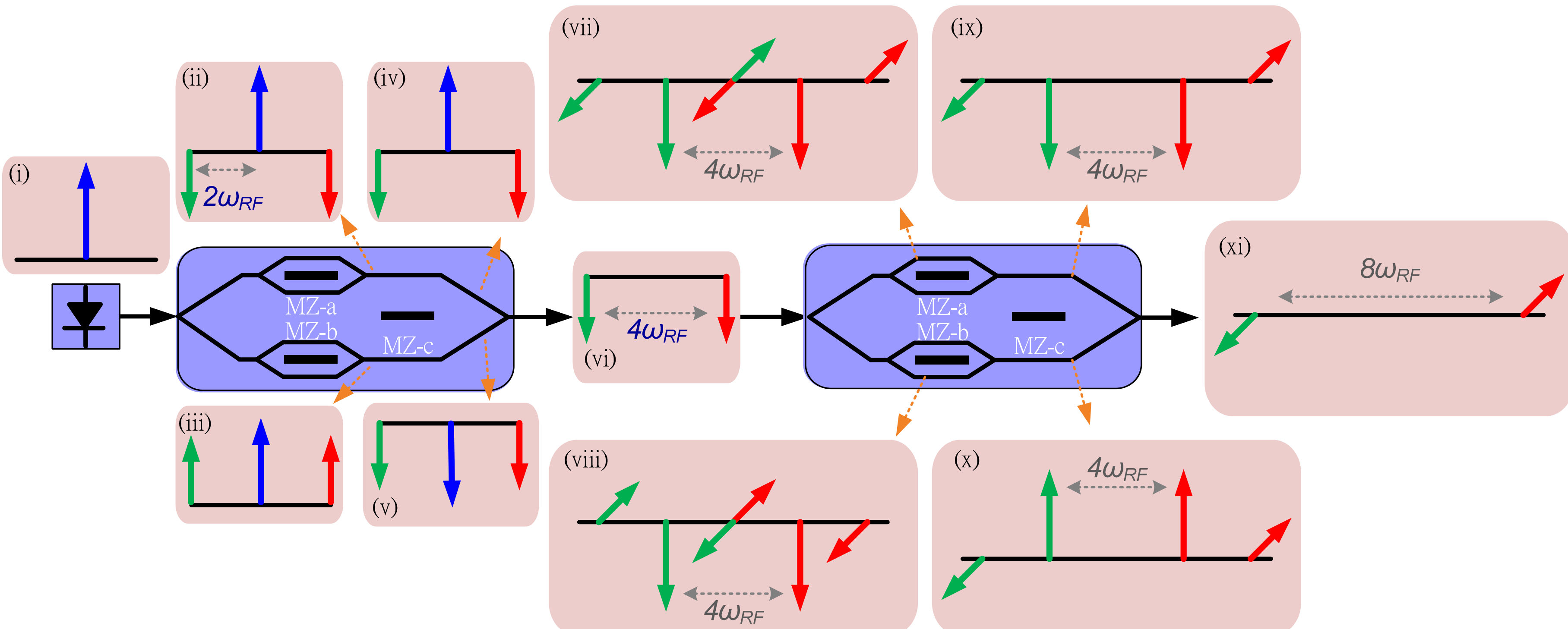
$$\square\square\square = \mathrm{Re}\,\square\square_{\square}\square^{\square\square 0\square} \cdot \cos\square\frac{\square\square}{\square_{\square}}\square\square = \square_{\square}\cos\square\square_{\square}\square\cos\square\square\ \square\square\square\square$$

and the optical power can be written as:

$$\square\ \square\ \Lambda\square\Lambda^2 = \Lambda\square_{\square}\Lambda^2\cos^2\square\square\ \square(\square)\square = \frac{1}{2}\Lambda\square_{\square}\Lambda^2\square 1 + \cos\square 2\square\ \square(\square)\square\square$$



Frequency Octuple Techniques

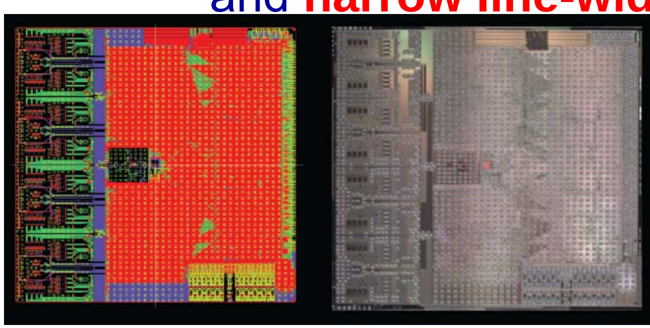


Advantages of OFDM Modulation Formats

- OFDM is a simple solution to signal dispersion and multi-path interferences in single carrier modulation
  - Multi-carrier modulation format
  - Increased efficiency because carrier spacing is reduced (orthogonal carriers overlap)
  - Equalization simplified
  - More resistant to fading
  - Now possible because of advances in **signal processing horsepower**
- Disadvantages of OFDM
  - Higher **peak-to-average power ratio** (PAPR) ⇨ IMD3
  - More sensitivity to phase noise, timing and frequency offset
  - Greater complexity
  - Efficiency gains reduces by requirement for guard interval

Optical OFDM

- The integration of optical and wireless network: optical OFDM RoF can provide
  - Seamless integration with wireless communication: no format conversion is needed
  - Offer a higher spectra efficiency modulation format
  - OFDM scales well as dispersion/bit rates increase
  - **Very efficient DSP implementation**
  - OFDM can correct for **linear** distortion: chromatic dispersion, 1st order PMD, and/or nonlinear distortion: SPM
- Optical OFDM
  - Coherent OFDM (CO-OFDM): required **phase tracking** (OPLL) and **narrow line-width** local laser source (LO)
  - npler transmitter and receiver design



Note: CMOS Rx-ASIC with 4x20 Gs/s A/D and 12 trillion operation per second. OFC 2008, tutorial NWC3

Optics express, 2008, Jan. pp. 873-879

OFDM: the "Standard" for Future Broadband Wireless System?

Frequency	Wireless System
2 GHz	UMTS / 3G Systems
2.4 GHz	IEEE 802.11 b/g WLAN (OFDM)
5 GHz	IEEE 802.11 a WLAN (OFDM)
2-11GHZ	IEEE 802.16 WiMAX (OFDM)
17/19GHz	Indoor Wireless (Radio) LANs
28 GHZ	Fixed wireless access – Local point to Multipoint (LMDS)
38 GHz	Fixed wireless access , Picocellular
58 GHz	Indoor wireless LANs
57-64 GHz	IEEE 802.15 WPAN
10-66 GHZ	IEEE 802.16 - WiMAX