Optical Links for Transmission of Microwave Signals

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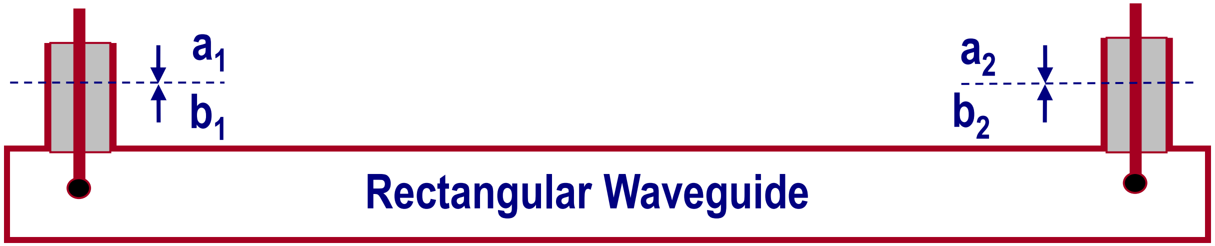
Outline of lecture:

1. Introduction
2. Scattering Matrix of Optical Analog Link
   A. Optical Analog Link as a two-port
   B. Transmitter with Direct Modulation
   C. Transmitter with External Modulation
   D. Photoreceiver
   E. Effects of fiber dispersion
   F. Gain of OAL
   G. OAL with coherent detection
3. Architecture of Transmission Links
4. Radio Over Fiber networks
5. Conclusions

- We have to transmit a microwave signal from point to point. We could use a few types of transmission lines.

a)

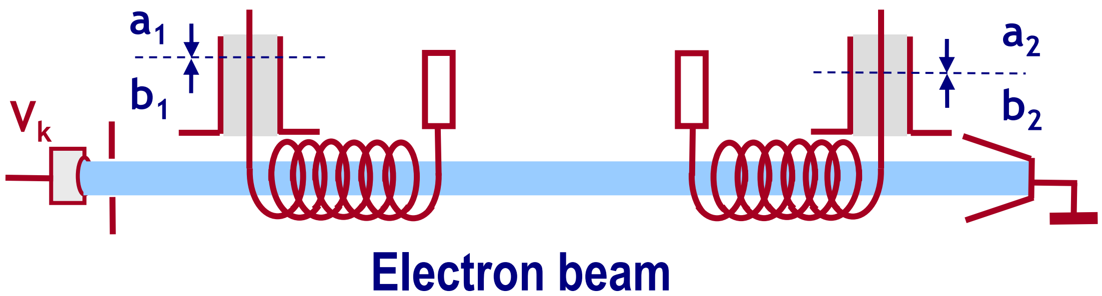


- We could use a rectangular waveguide, or free space between antennas.

b)

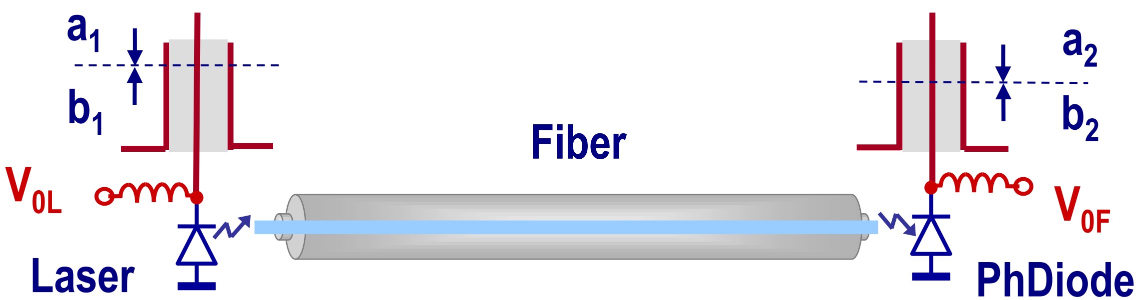
- Travelling Wave Tube uses electron beam as a transmission line.

c)

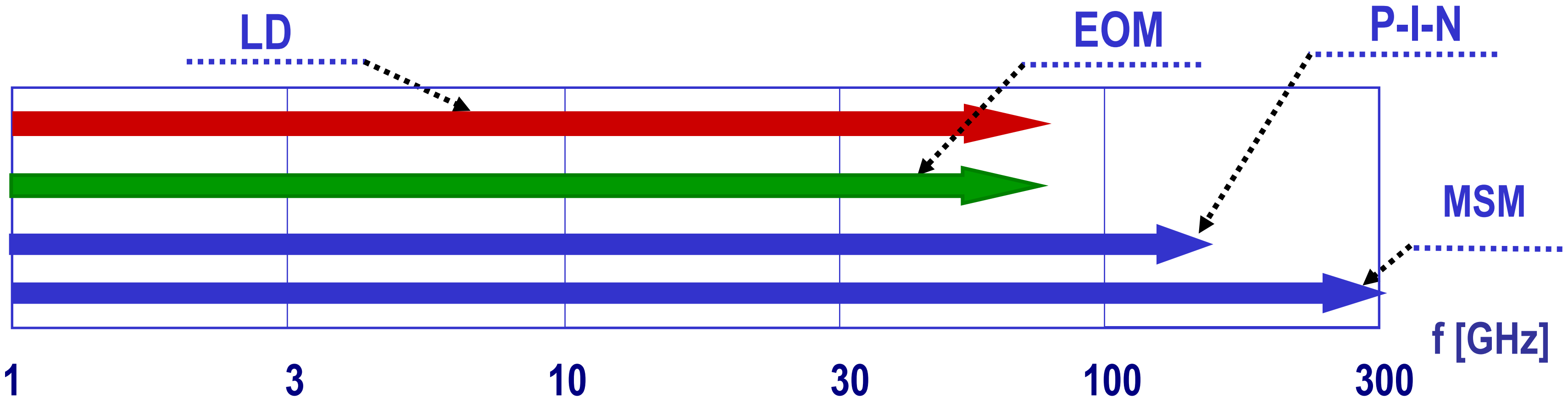


- Fiber with optical beam is a very good microwave transmission line.

d)

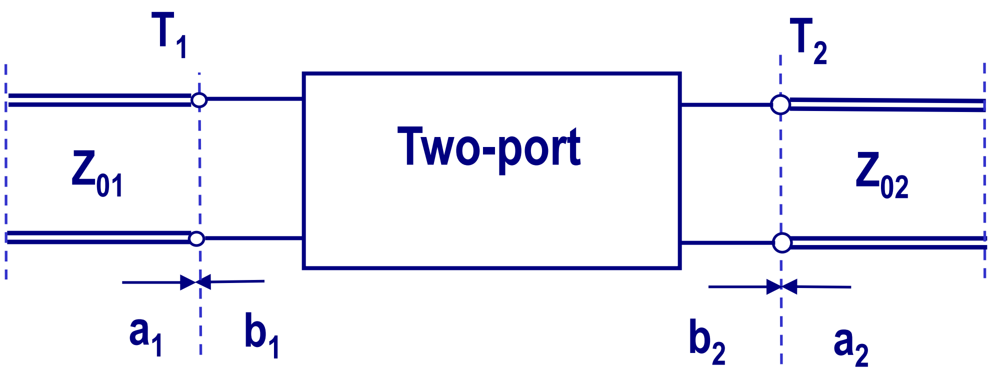


- Modulation frequency of laser diodes LD is limited to the 60 GHz by the internal resonance between the electrons and photons.
  - The push-pull principle solves partially these problems.
- Two types of the external optical modulators are widely used:
  - The electro-optic (EOM) travelling wave $LiNbO_3$ Mach-Zender modulators,
  - Electro-absorption (EAM) optical modulators.
- The new types of travelling-wave PIN photodectors have moved the bandwidth above 100 GHz .
- Metal-Semiconductor-Metal photodetectors have banwidth above 300 GHz.



2A. Optical Analog Link as a two-port (a)

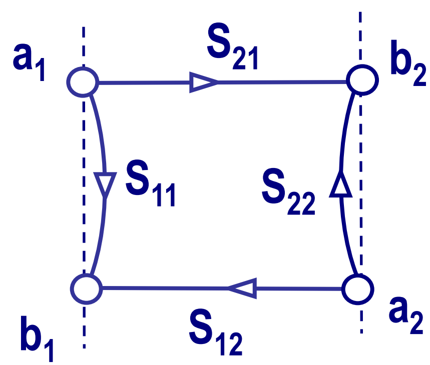
- Scattering matrix is simply defined for two-port circuit.



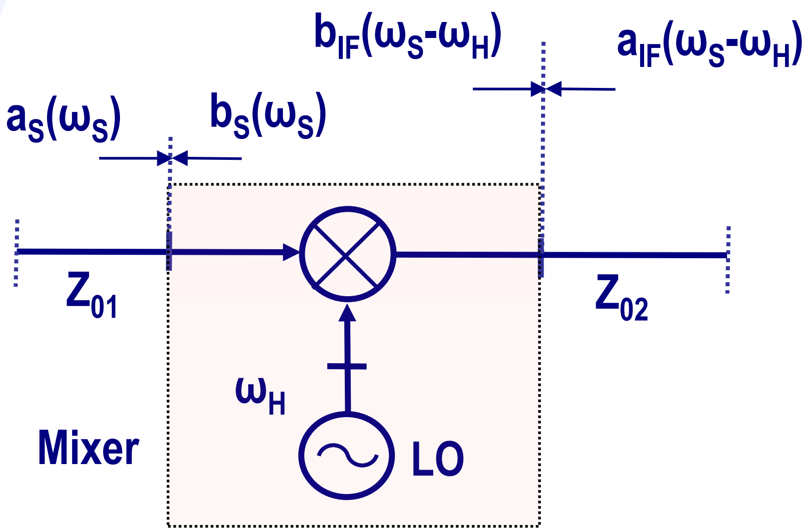
$$a_1 = \frac{U_{p1}}{\sqrt{Z_{01}}}; \quad a_2 = \frac{U_{p2}}{\sqrt{Z_{02}}};$$

$$b_1 = \frac{U_{w1}}{\sqrt{Z_{01}}}; \quad b_2 = \frac{U_{w2}}{\sqrt{Z_{02}}};$$

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix};$$



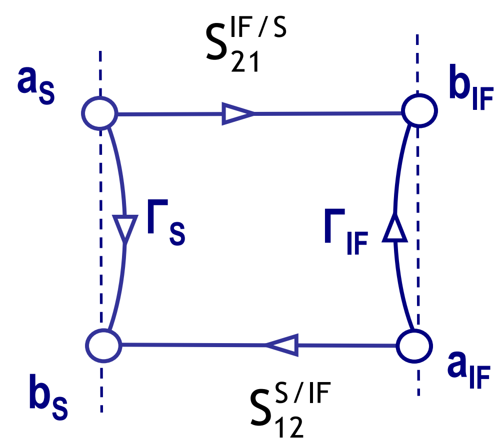
- Scattering matrix could also be defined for mixer.



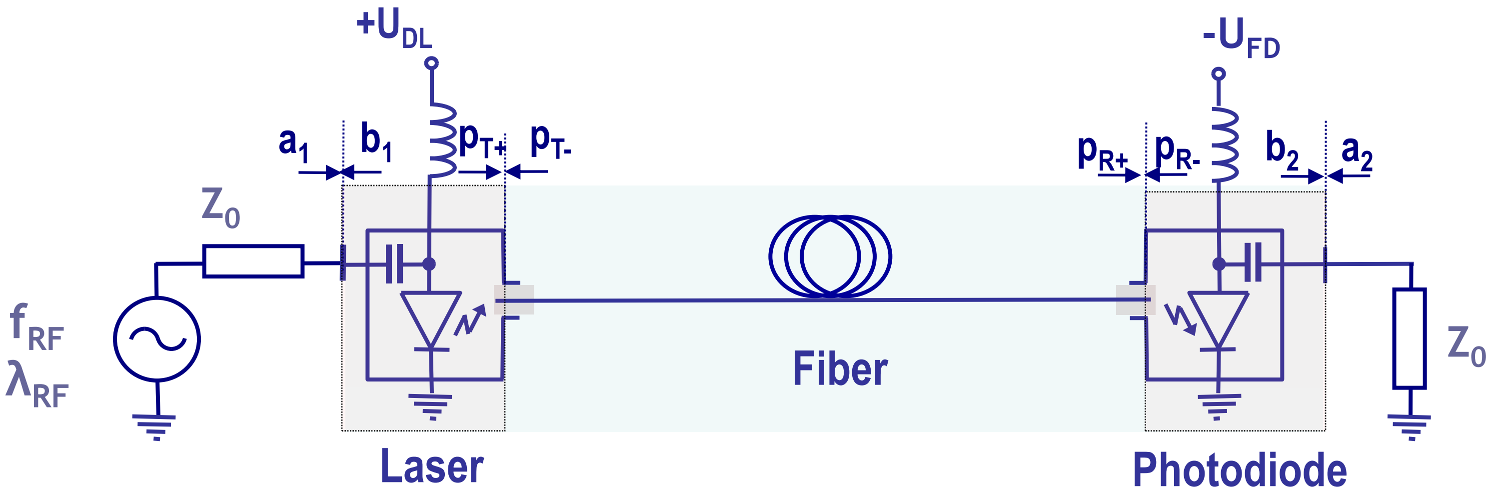
$$b_S(\omega_S) = S_{11}^{S} a_S(\omega_S) + S_{12}^{S/IF} a_{IF}(\omega_S - \omega_H);$$

$$b_{IF}(\omega_S - \omega_H) = S_{21}^{IF/S} a_S(\omega_S) + S_{22}^{IF} a_{IF}(\omega_S - \omega_H);$$

$$\begin{bmatrix} b_S \\ b_{IF} \end{bmatrix} = \begin{bmatrix} S_{11}^{S} & S_{12}^{S/IF} \\ S_{21}^{IF/S} & S_{22}^{IF} \end{bmatrix} \begin{bmatrix} a_S \\ a_{IF} \end{bmatrix};$$

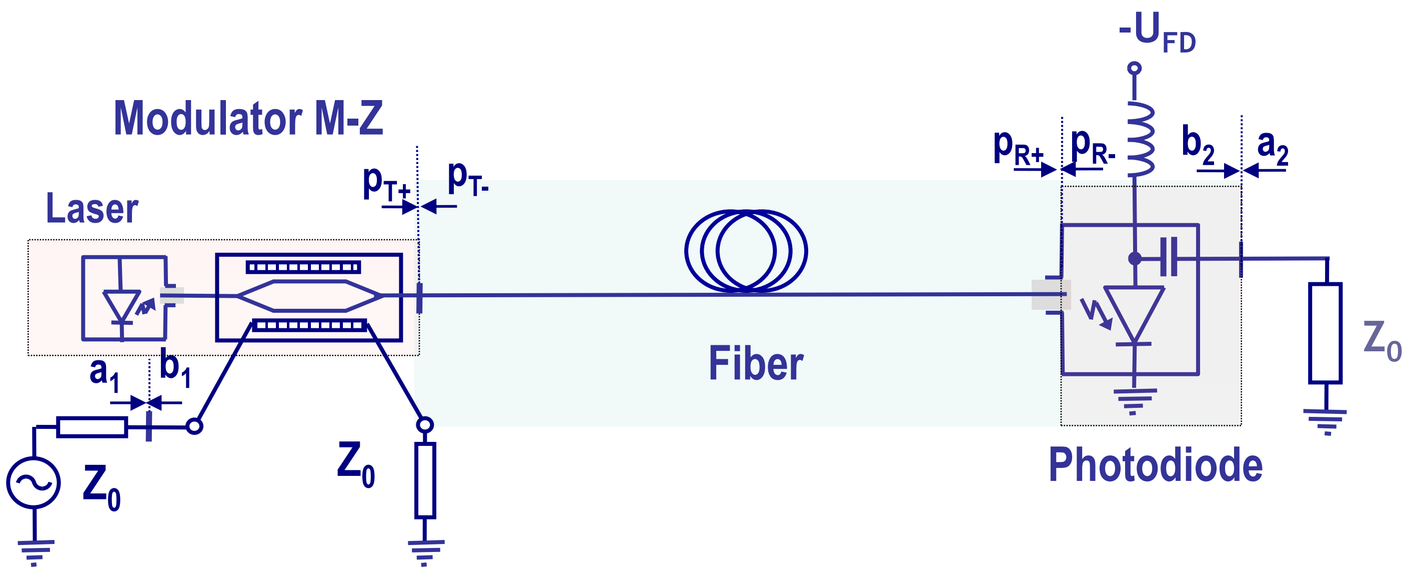


- The simple circuit of analog optical link with direct modulation of optical power



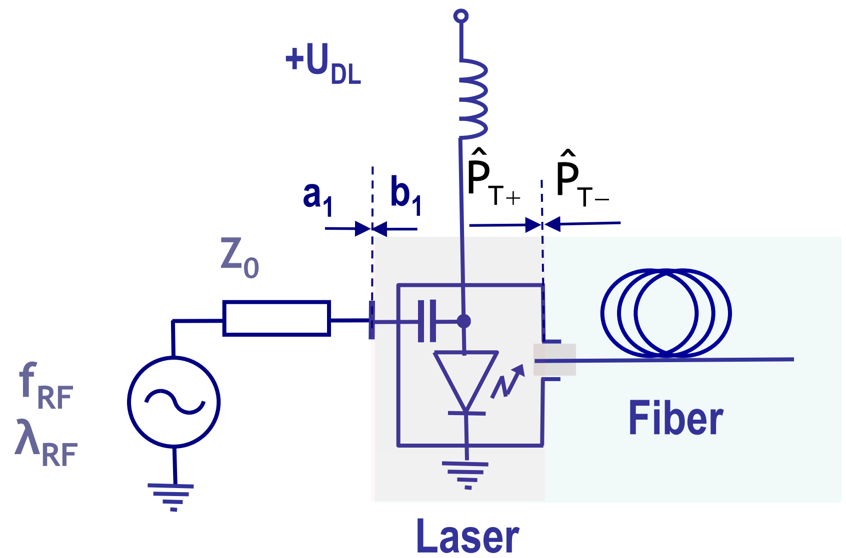
$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = [S] \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix};$$

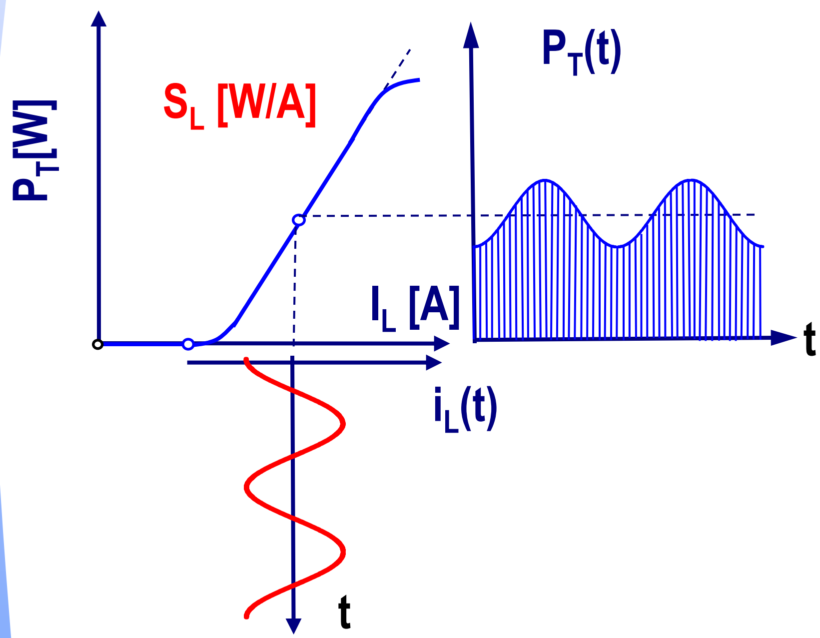
- The circuit of analog optical link with external modulation of optical power.



$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = [S]\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}\begin{bmatrix} a_1 \\ a_2 \end{bmatrix};$$

- Transmitter with laser –
  - microwave input signal and optical output signal.





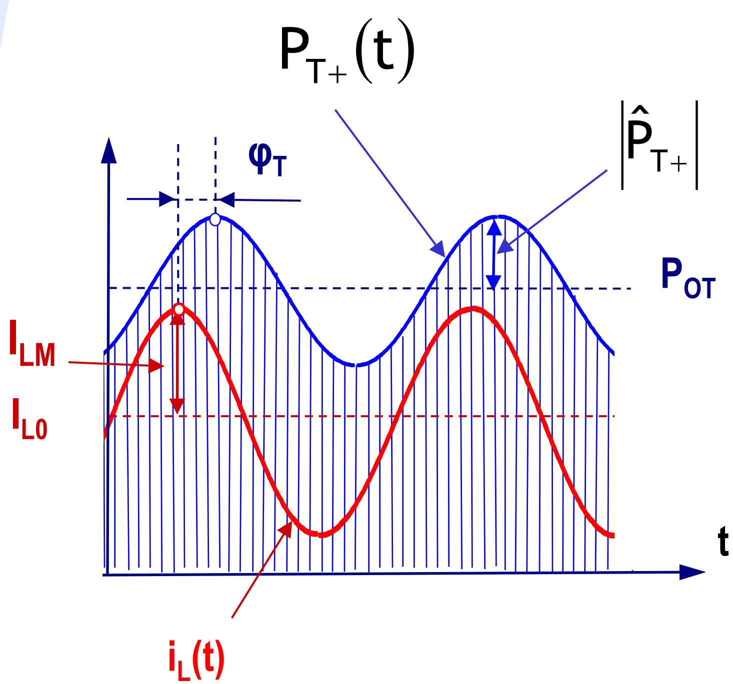
$$i_L(t) = I_{L0} + I_{LM}\cos(\omega_{RF}t + \varphi_0);$$

$$P_{T+}(t) = P_{0T}[1 + m\cos(\omega_{RF}t + \varphi_0)];$$

$$S_L = \frac{mP_{0T}}{I_{LM}};$$

2B. Transmitter with Direct Modulation (b)

- Phasors describe better the problem of modulation

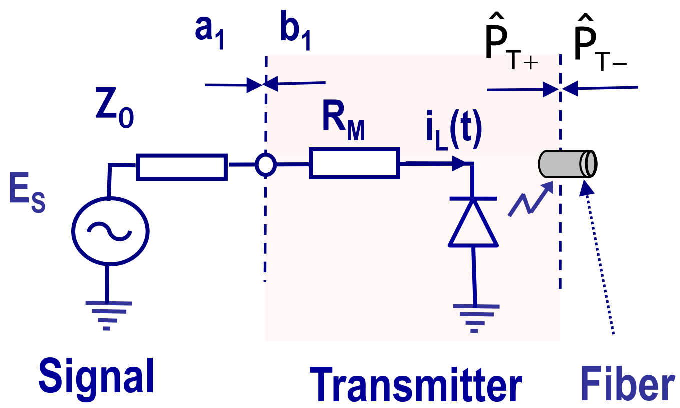


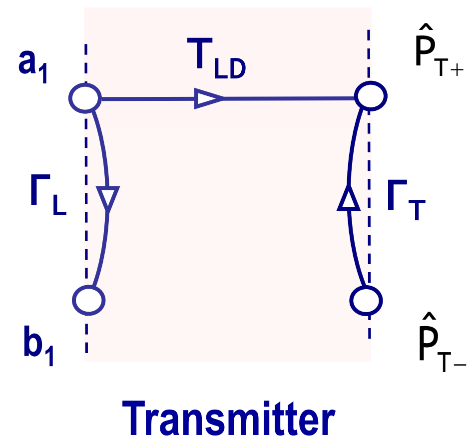
$$i_L(t) = I_{L0} + \mathrm{Re}\left\{\hat{I}_{LM} e^{j\omega_{RF} t}\right\};$$

$$P_{T+}(t) = P_{0T} + \mathrm{Re}\left\{\hat{P}_{T+} e^{i\omega_{RF} t}\right\};$$

$$\hat{S}_L(\omega_{RF}) = \frac{\hat{P}_{T+}}{\hat{I}_{LM}} = M(\omega) S_L;$$

❑ Scattering matrix of optical transmitter with direct modulation





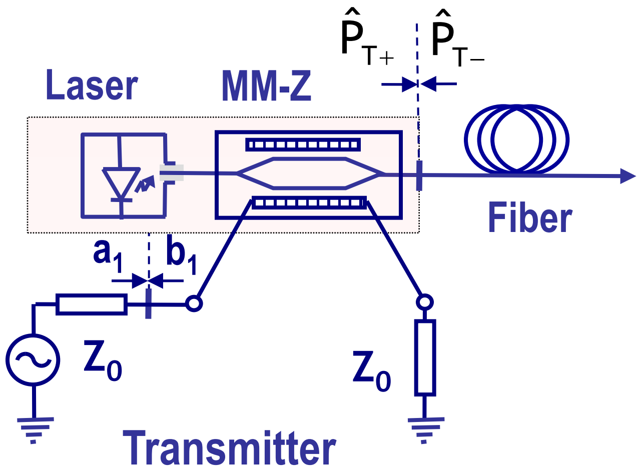
$$b_1 = a_1\Gamma_{LD};$$

$$\hat{P}_{T+} = a_1 T_{LD} + \hat{P}_{T-}\rho_{LD};$$

$$T_{LD}\big|_{\hat{P}_{T-}=0} = \frac{\hat{P}_{T+}}{a_1} = \frac{\hat{P}_{T+}}{\hat{I}_{LM}}\frac{\hat{I}_{LM}}{a_1} = \hat{S}_L\frac{\hat{I}_{LM}}{a_1};$$

Circuit parameter

- For transmitter with external modulator M-Z power of optical output signal is the function of amplitude of microwave signal and power of laser.



$$P_{T+}(t) = P_{0T} + \mathrm{Re}\left\{\hat{P}_{T+} e^{i\omega_{RF}t}\right\};$$

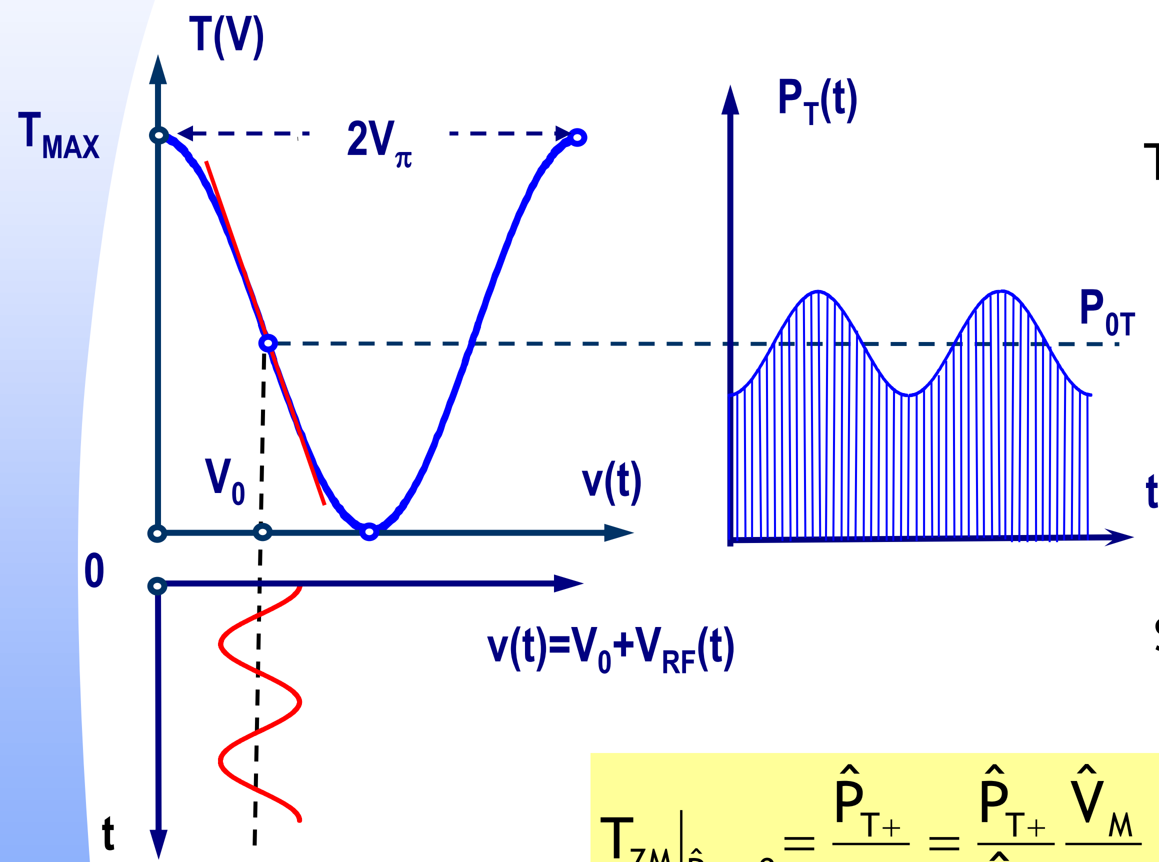
$$P_S = \frac{V_M^2}{2Z_0} = \frac{|a_1|^2}{2}; \qquad \hat{V}_M = a_1 Z_0;$$

$$b_1 = a_1 \Gamma_{ZM};$$

$$\hat{P}_{T+} = a_1 T_{ZM} + \hat{P}_{T-}\rho_{ZM};$$

$$\hat{S}_{MZ}(\omega_{RF}) = \frac{\hat{P}_{T+}}{\hat{V}_M};$$

- Illustration of modulation process of optical power transmitted by M-Z modulator

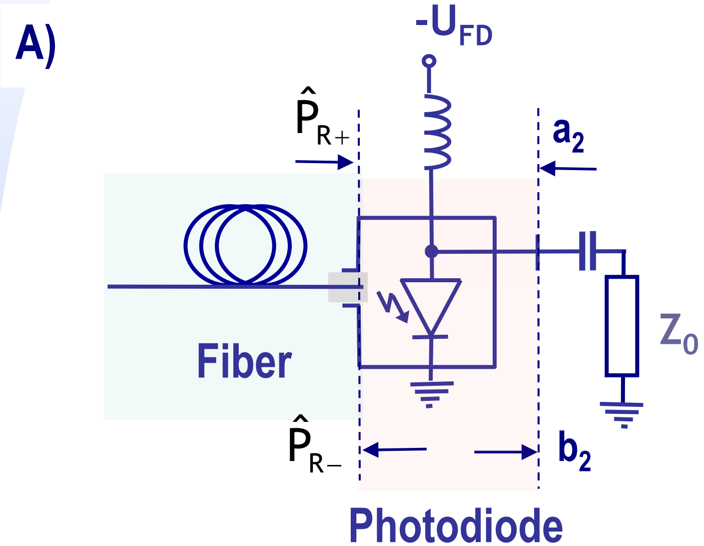


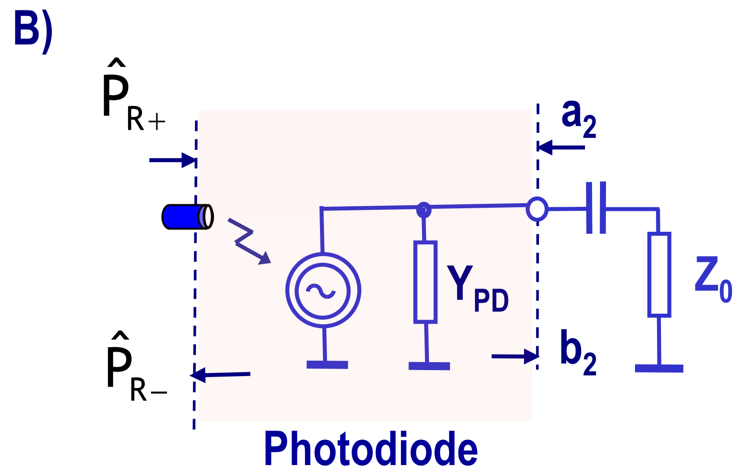
$$T(V)=\frac{T_{MAX}}{2}\left\{1+\cos\left[\frac{\pi v_M(t)}{2V_\pi}\right]\right\};$$

$$S_{MZ}=\left.\frac{\partial[T(V)/T_{MAX}]}{\partial V}\right|_{V=V_\pi/2}=-\frac{\pi}{2V_\pi};$$

$$T_{ZM}\Big|_{\hat{P}_{T-}=0}=\frac{\hat{P}_{T+}}{a_1}=\frac{\hat{P}_{T+}}{\hat{V}_M}\frac{\hat{V}_M}{a_1}=\hat{S}_{MZ}\sqrt{Z_0};$$

❑ Scattering matrix of optical receiver

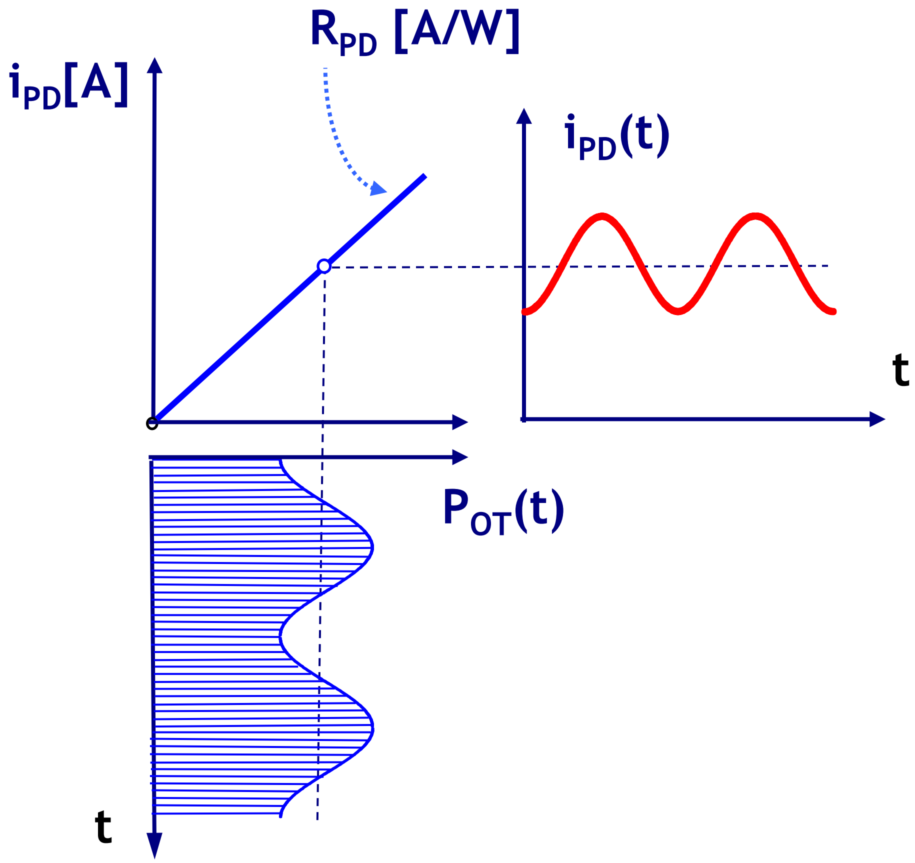




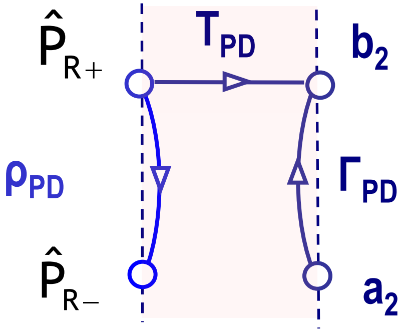
$$\hat{P}_{R-} = \hat{P}_{R+}\rho_{PD};$$

$$b_2 = \hat{P}_{R+}T_{PD} + a_2\Gamma_{PD};$$

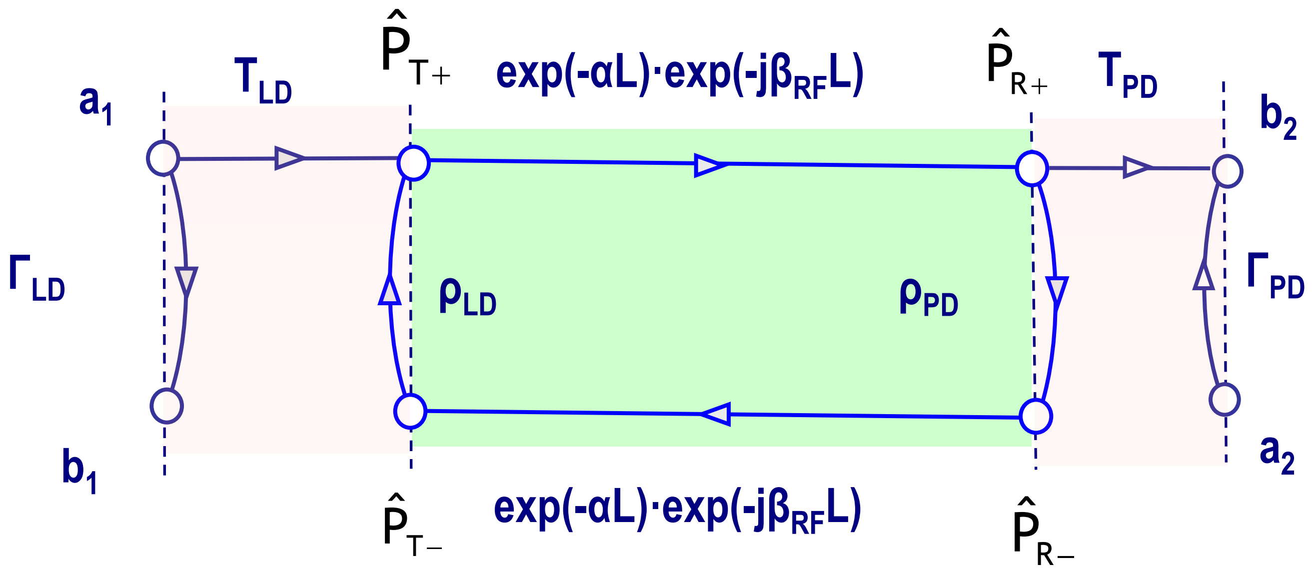
❑ Illustration of detection of optical signal



$$T_{PD} = \frac{b_2}{\hat{P}_{R+}} = \frac{\sqrt{Z_0}\hat{R}_{PD}}{y_{PD}+1};$$



- Flow graph for analog optical link



$$[S] = \begin{bmatrix} \Gamma_{ND} & 0 \\ G_{OL} & \Gamma_{PD} \end{bmatrix};$$

$$G_{OL} = \frac{T_{ND} T_{PD} e^{-\alpha L} e^{-j\beta_{RF} L}}{1 - \rho_{ND} \rho_{PD} e^{-2\alpha L} e^{-j2\beta_{RF} L}};$$

- Dispersion of fiber causes interesting and important effect when amplitude modulated signal is transmitted.

$$P_{T+}(t) = P_{0T}\left[1 + m\cos(2\pi f_{RF} t)\right];$$

$$E_{T+}(t) \approx \sqrt{P_{0T}}\left[1 + \frac{m}{2}\cos(2\pi f_{RF} t)\right]\mathrm{Re}\left\{e^{j2\pi f_0 t + \varphi_0}\right\};$$

- 3 components of EM field with different frequencies travel with different group velocities because of dispersion.

$f_0 - f_{RF}$, f_0, $f_0 + f_{RF}$

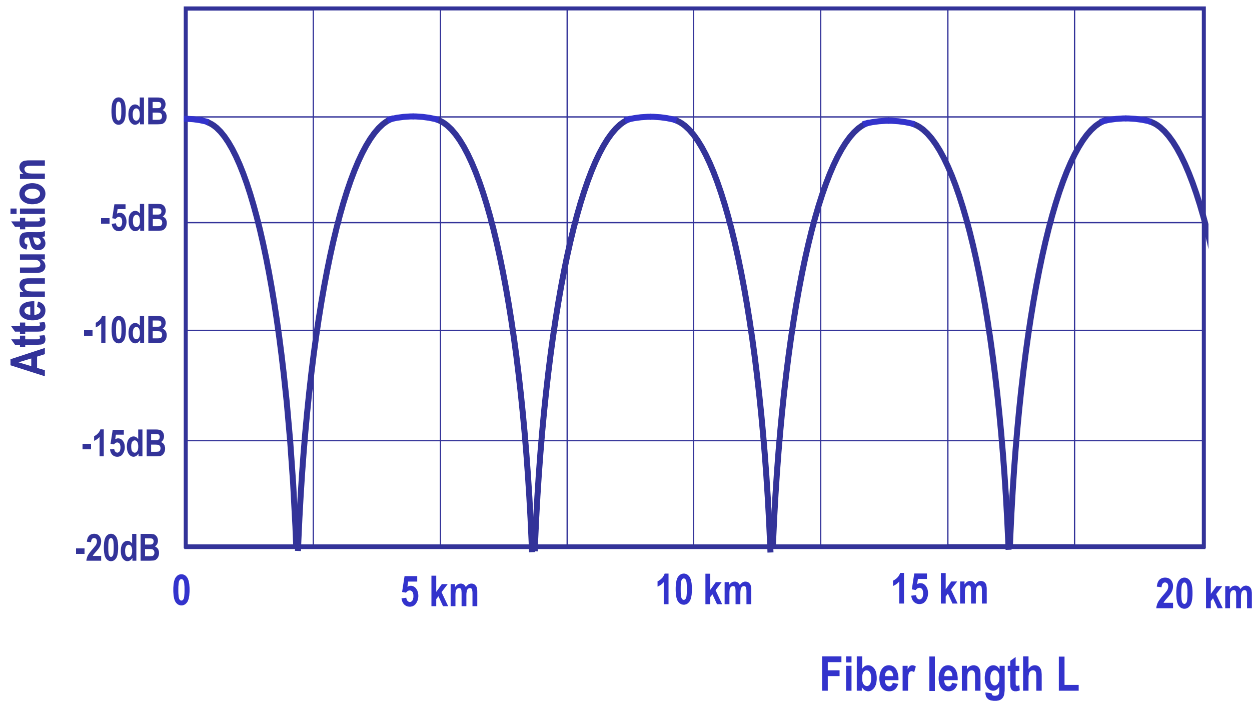
- Because of interference of sidebands modulation may disappear.

$$P_{T+}(t) = P_{0T}\left[1 + m\cos\left(\frac{\pi L}{c}\lambda_0^2 D f_{RF}^2\right)\cos\left[2\pi f_{RF}\left(t - \frac{L}{v_g}\right)\right]\right];$$

2E. Effects of fiber dispersion (b)

- Illustration of dispersion effect for directly modulated optical signal transmitted via fiber.
- Modulated power periodically vanishes with period L_T.

$$L_T = \frac{c}{\pi \lambda_0^2 D f_{RF}^2};$$



f_{RF}=40 GHz
D=17ps/nm.km

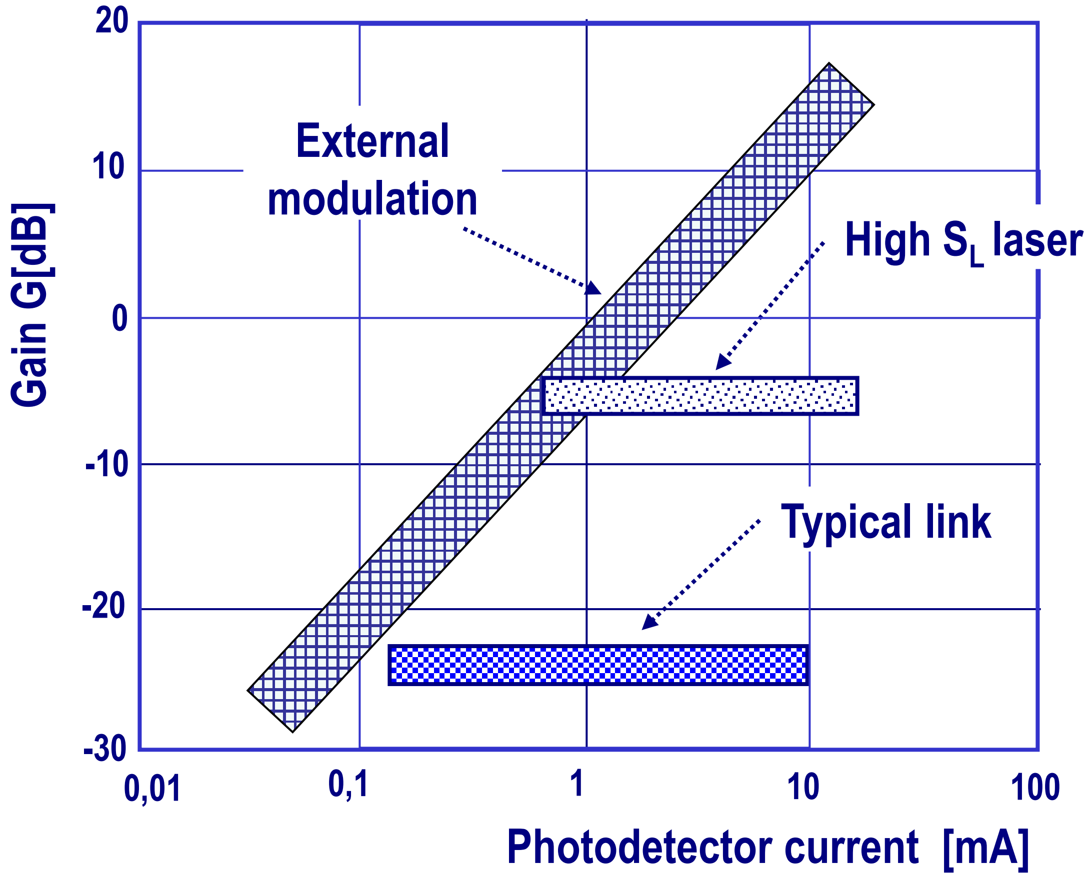
- Gain of analog link with direct intensity modulation of laser optical power

$$G_{OL}\left(\omega_{RF} \approx 0, L = 0\right) = S_L^2 R_{PD}^2;$$

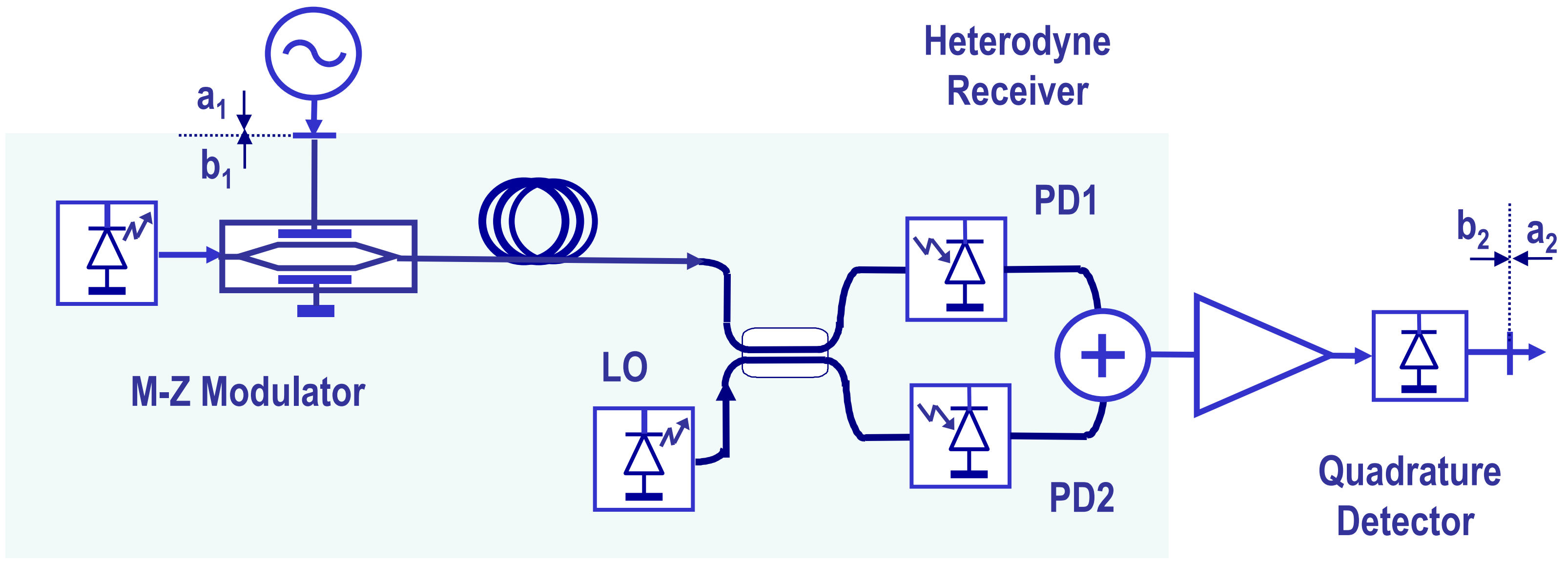
- Gain of analog link with external intensity modulation of laser optical power

$$G_{OL}\left(\omega_{RF} \approx 0, L \approx 0\right) \approx S_{MZ}^2 R_{PD}^2 \approx \frac{P_{0T}^2}{V_\pi^2} R_{PD}^2;$$

- Gain of analog link with direct and external electro-optical modulations

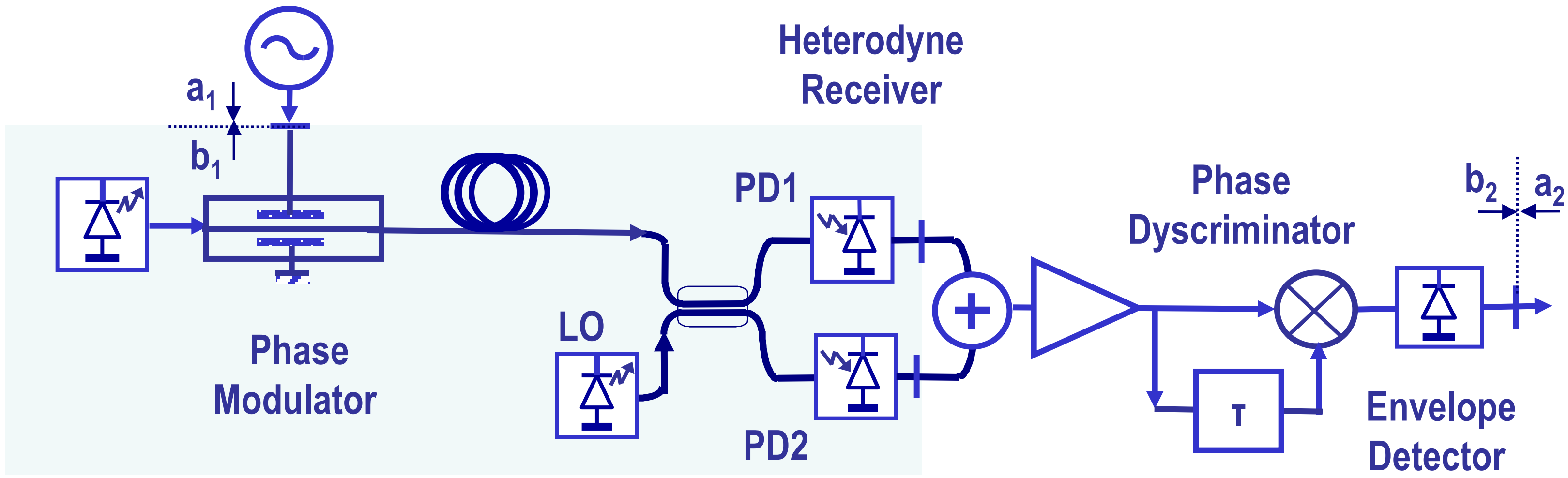


- OAL with heterodyne receiver needs the quadrature detector.

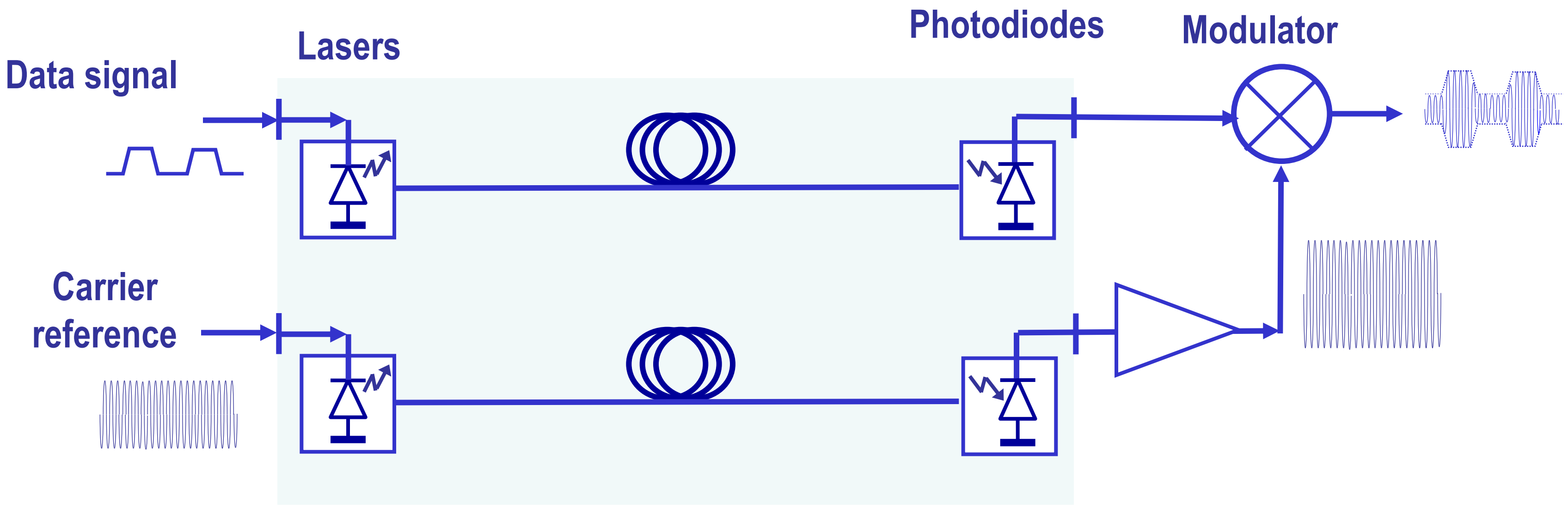


2G. OAL with coherent detection (b)

- Very good parameter are obtained for heterodyne receiver with phase modulator.

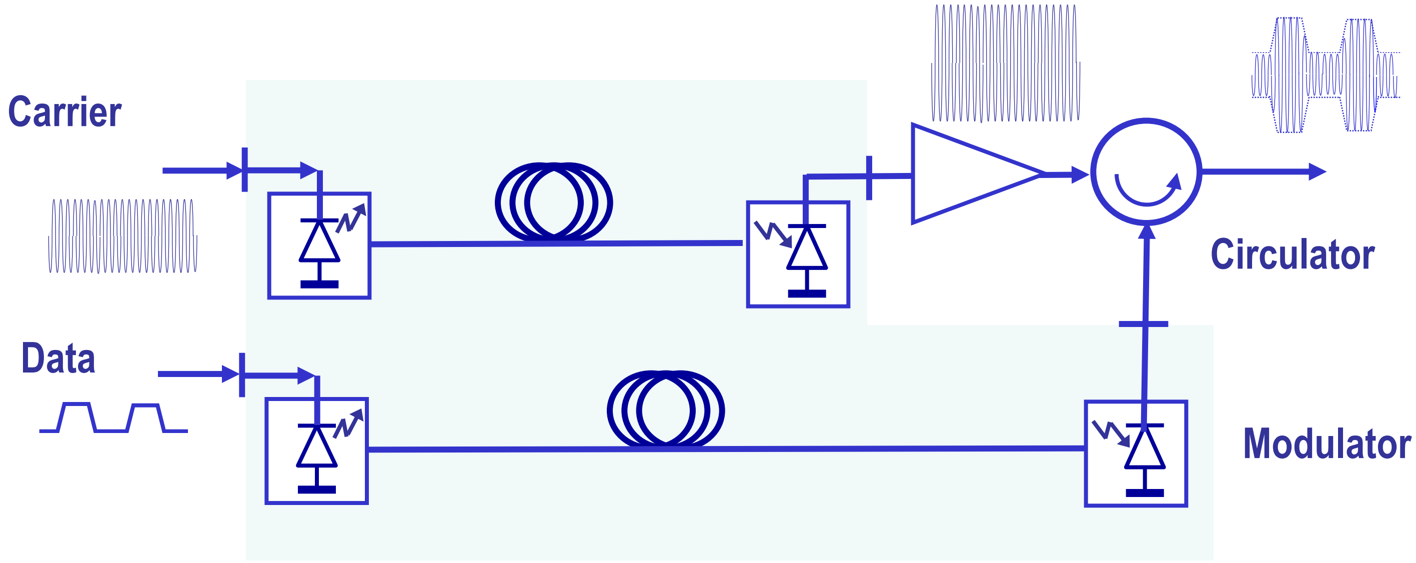


- The date signal and carrier are transmitted separately over different FO links.
- Separation of signals can significantly increase dynamic range.



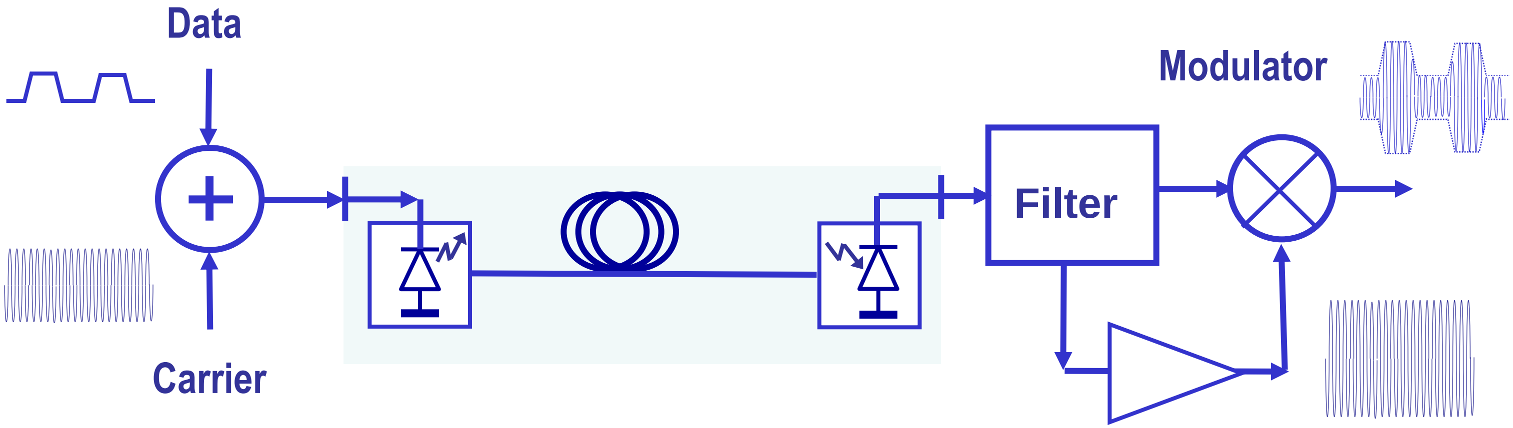
3. Architecture of Transmission Links (b)

- Data and carrier are transmitted separately.
- The photodiode is used as μW modulator. This solution reduces numbers of elements and local oscillator power



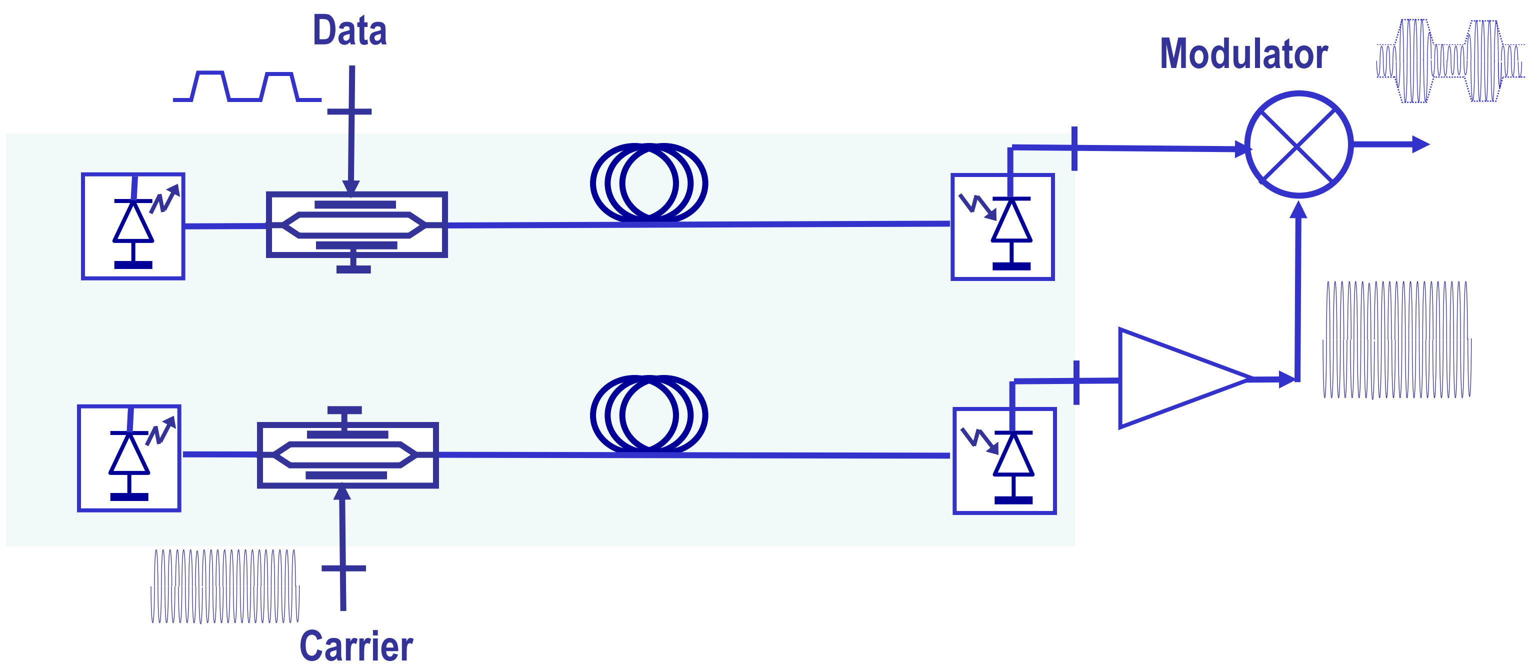
3. Architecture of Transmission Links (c)

- The photo-detector output signal is filtered and carrier reference signal is separated, next amplified and directed to the μW mixer



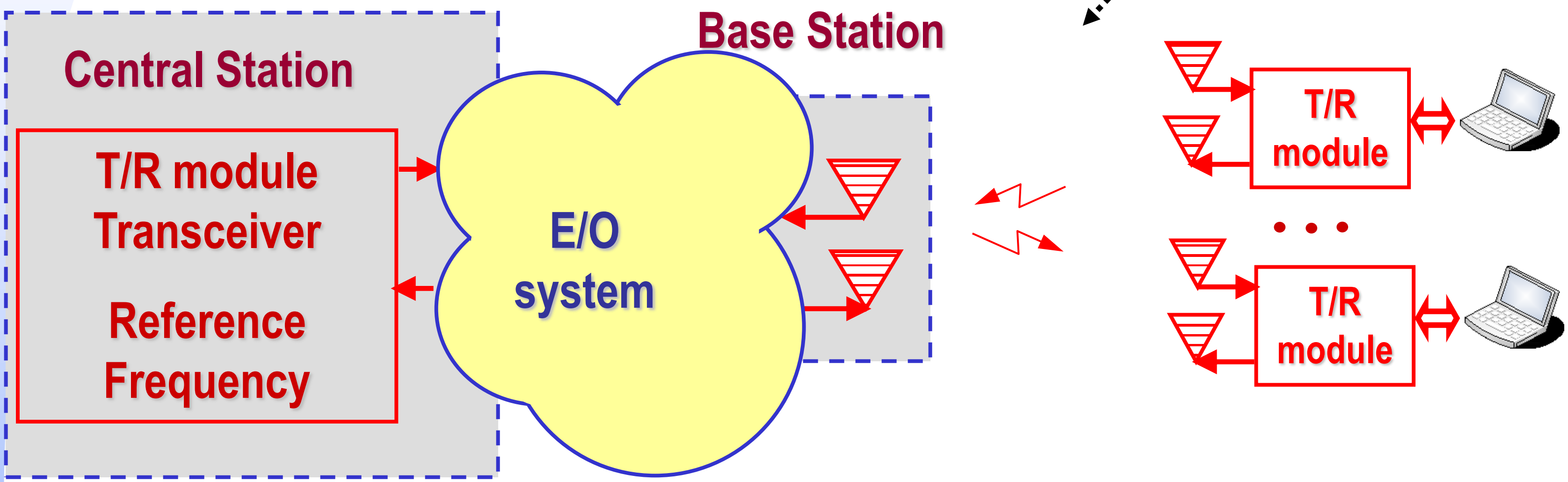
3. Architecture of Transmission Links (d)

- The structure of the circuit was discussed earlier, external modulator is also used.



How transmit reference frequency from Central Station to the Base Stations?

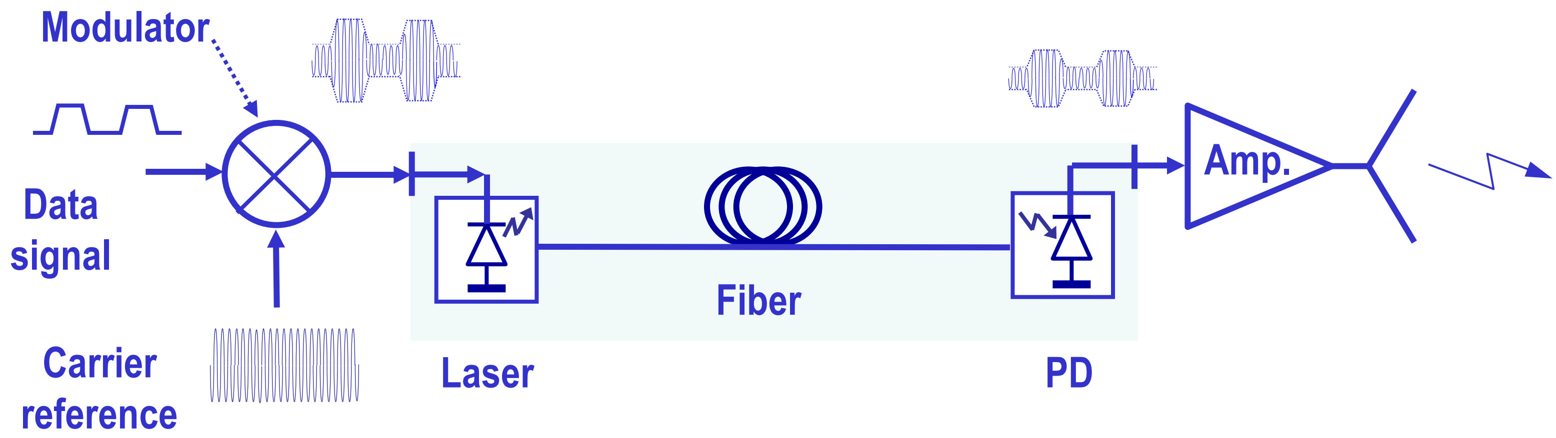
$f_{opt.carrier} = 60$ GHz



- **A** Direct transmission of carrier
- **B** Optical mixing
- **C** Multiplication of frequency
- **D** Phase Locked Loop – PLL technique

- Fiber is used as the transmission line between Central Station and Base Station.

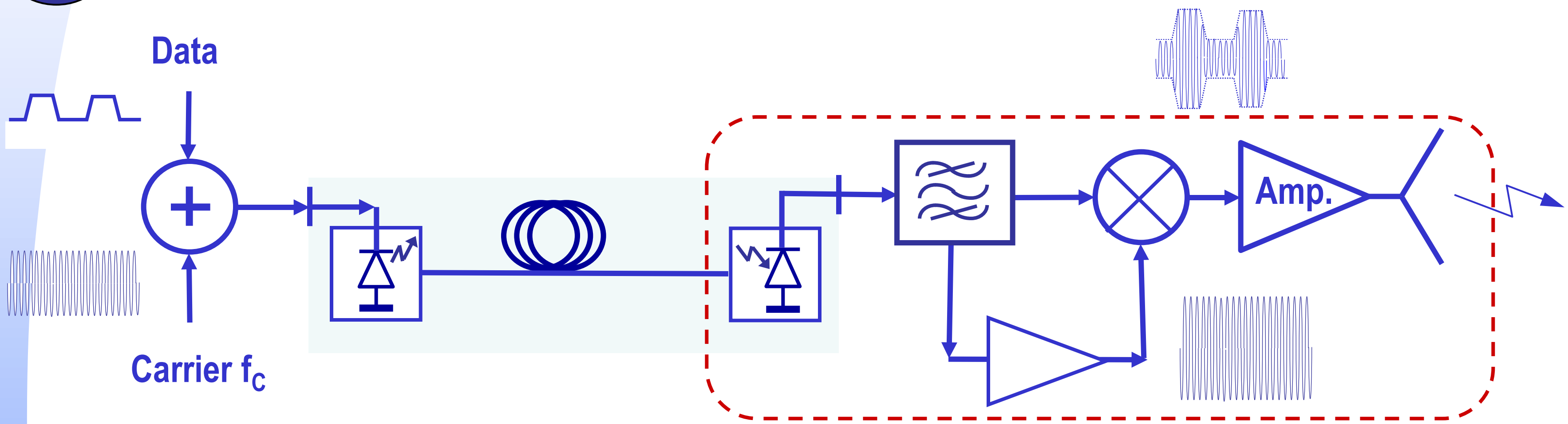
A



- A conventional OAL link in which the data signal is up-converted by the MMW carrier reference before laser bias current modulation

- The Data and Carrier are transmitted separately.

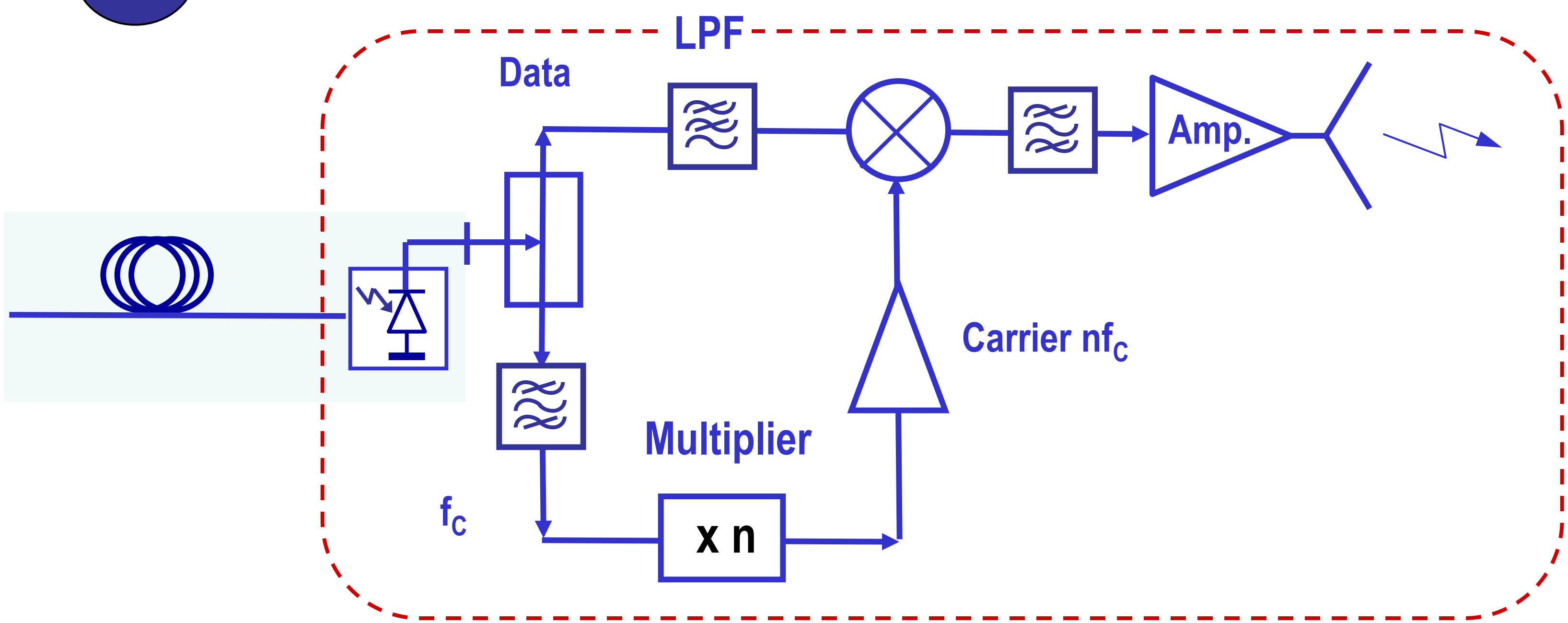
A



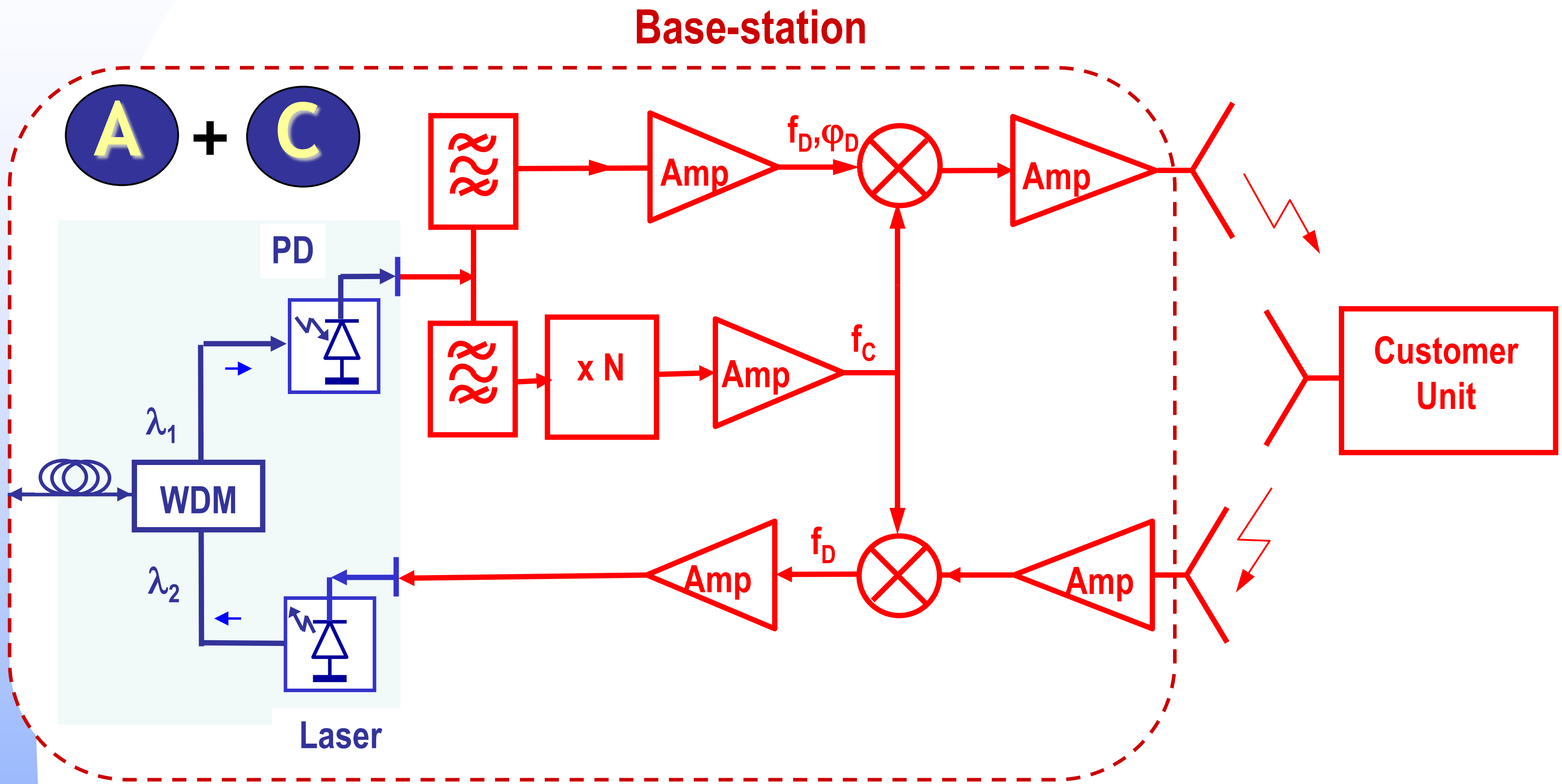
- The photo-detector output signal is filtered and carrier reference signal is separated, next amplified and directed to the microwave mixer

- The frequency f_C optically transmitted carrier is multiplied n times.
- After modulation and filtration the signal is directed to the antenna.

A + C



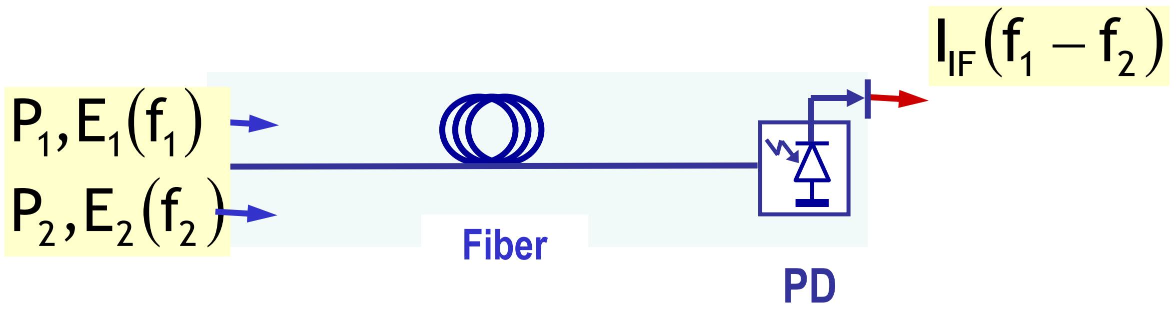
7,5 GHz x 8 = 60 GHz



Block diagram of base-station circuit with multiplication of carrier frequency for full-duplex, mm-wave fiber-radio network

B Generation by optical mixing

- Two optical signals (EM fields):



- The first signal:

$$E_1 = \mathrm{Re}\left\{A_1 e^{j2\pi f_1 t}\right\} = \mathrm{Re}\left\{|A_1| e^{j(2\pi f_1 t + \varphi_1)}\right\};$$

- The second signal - local oscillator:

$$E_2 = \mathrm{Re}\left\{A_2 e^{j2\pi f_2 t}\right\} = \mathrm{Re}\left\{|A_2| e^{j(2\pi f_2 t + \varphi_2)}\right\};$$

- Photodetector is responsive to the photon flux, is insensitive to the optical phase.
- The signal directed to the photodetector:

B

$$E = E_1 + E_2;$$

$$P \approx |E_1 + E_2|^2;$$

- Photocurrent I_{PD} is proportional to the incident power P and detector's sensitivity R:
- P_1 and P_2 are the powers, f_{IF} is intermediate frequency.

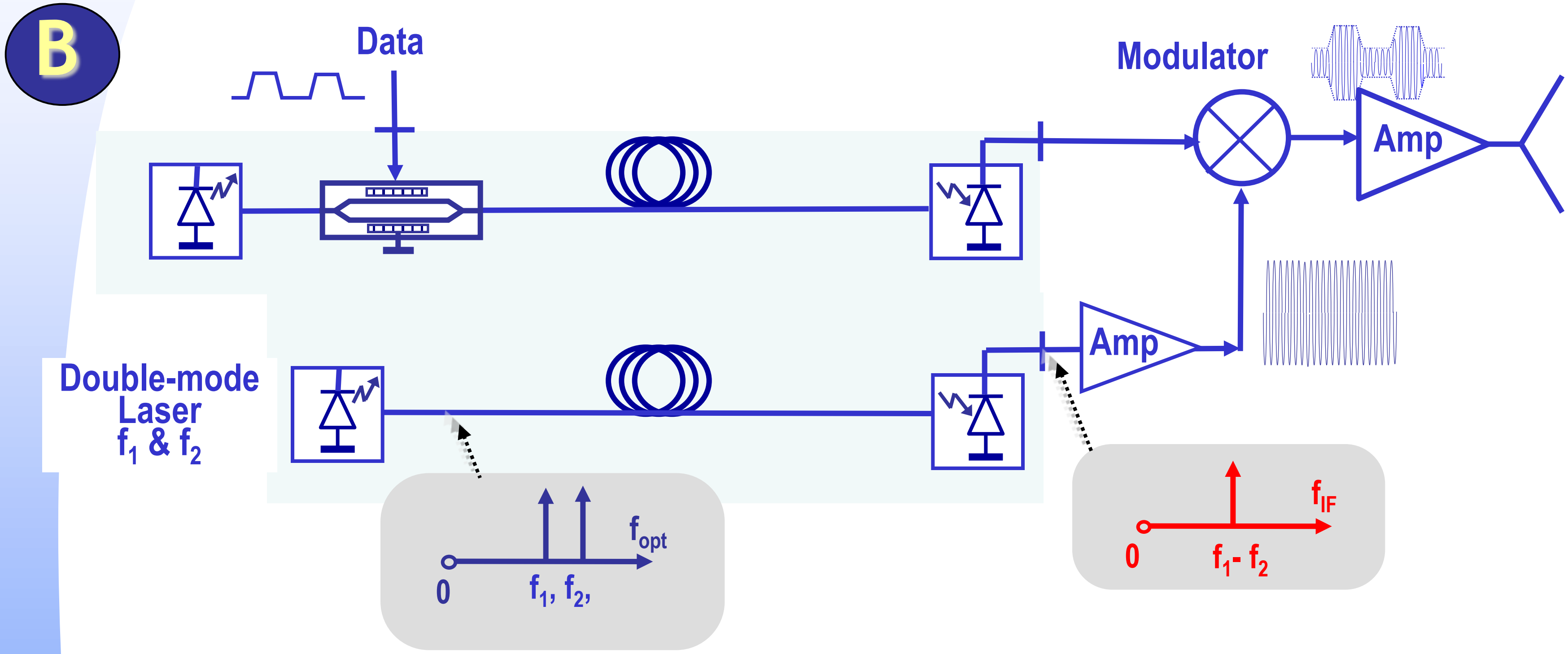
$$f_{IF} = |f_1 - f_2|;$$

$$I_{PD} = RP = R\left\{P_1 + P_2 + 2\sqrt{P_1P_2}\cos\left[2\pi f_{IF}t + (\varphi_1 - \varphi_2)\right]\right\};$$

- The name of the process: optical mixing, optical heterodyning, photomixing, coherent optical detection.

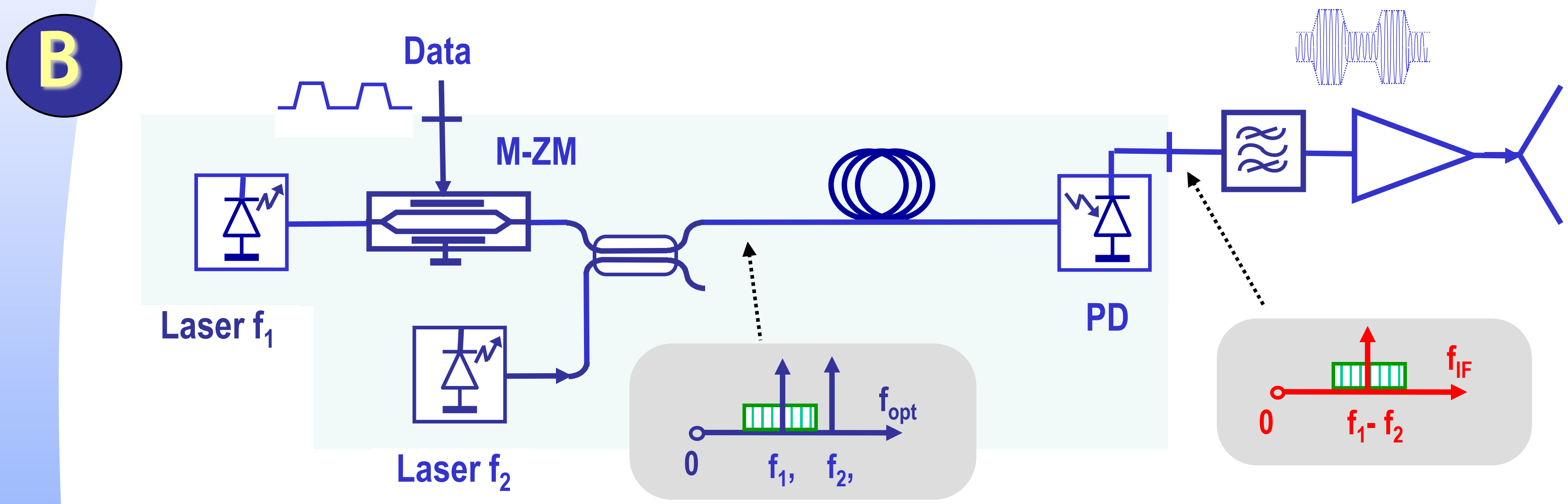
$$I_{IF} = 2R\sqrt{P_1P_2}\cos\left[2\pi f_{IF}t + (\varphi_1 - \varphi_2)\right];$$

- A specially constructed modified distributed feedback laser (DFB) in which oscillation occurs simultaneously on two frequencies, for two modes f_1 and f_2.



- The mode separation and frequency f_{IF} is adjusted to the desired value by proper choosing the grating strength coefficient.

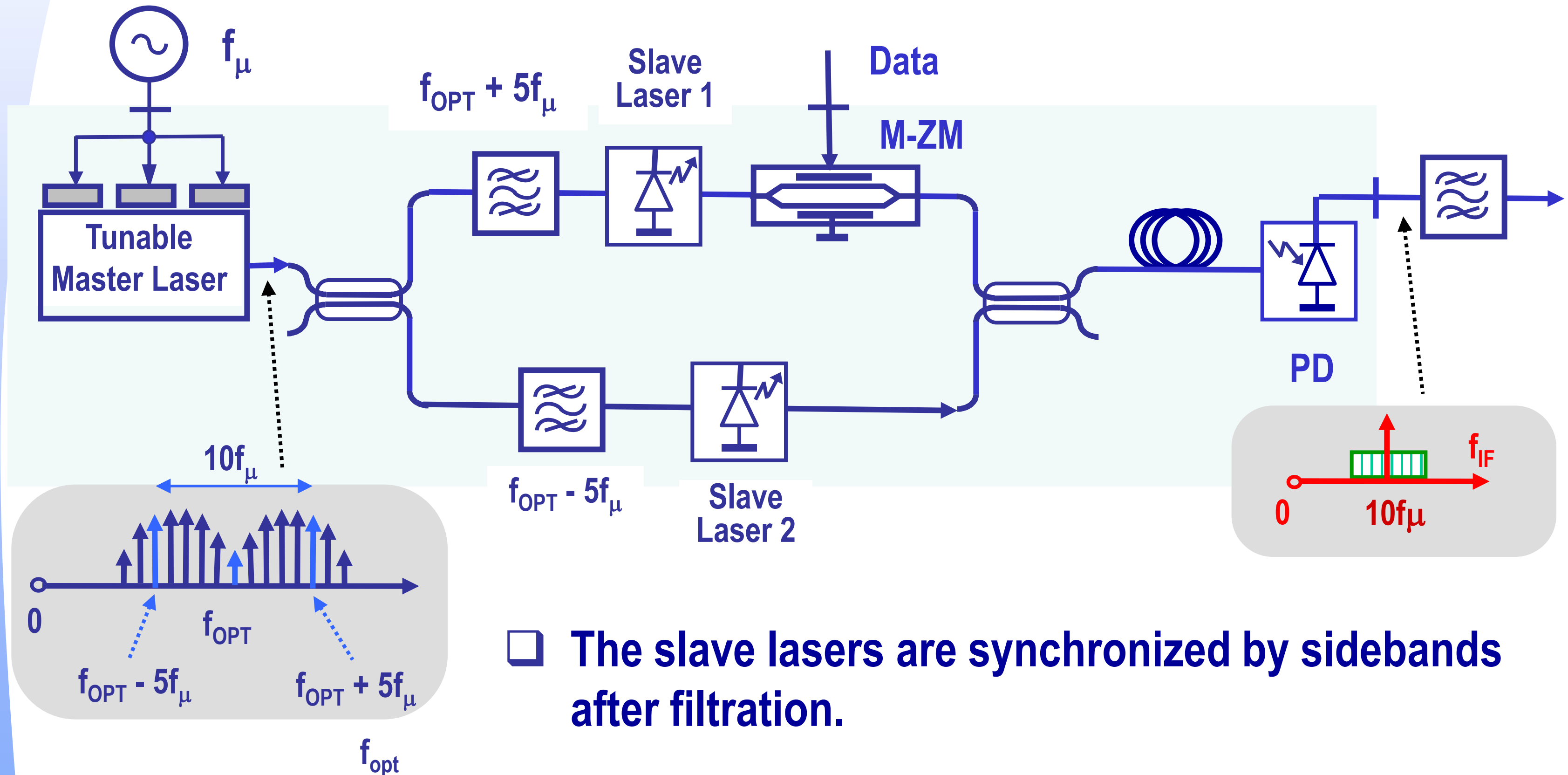
- Process of optical mixing with 2 lasers with frequency f_1 and f_2, to transmit the optical signals by fiber to a photodiode and to extract the intermediate frequency f_{IF}.



- One optical signal is modulated by data.
- The spectrum of optical signals must be "pure", f_{IF} is automatically controlled.

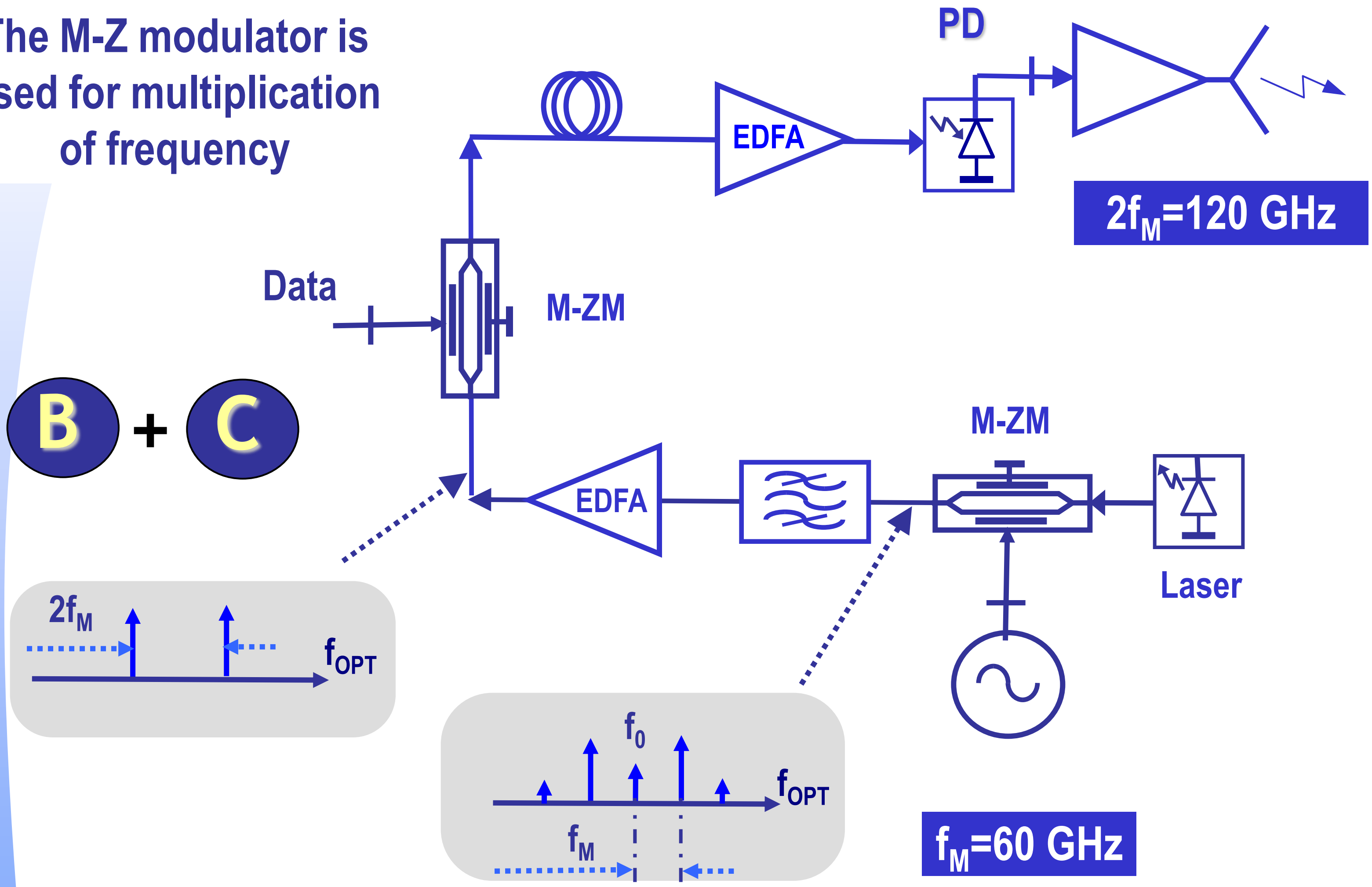
4. Radio over fiber networks (j)

- The spectral purity of the microwave signal may be really improved by synchronization of the laser action.
- The master laser is tuned by stable microwave source of frequency f_μ.

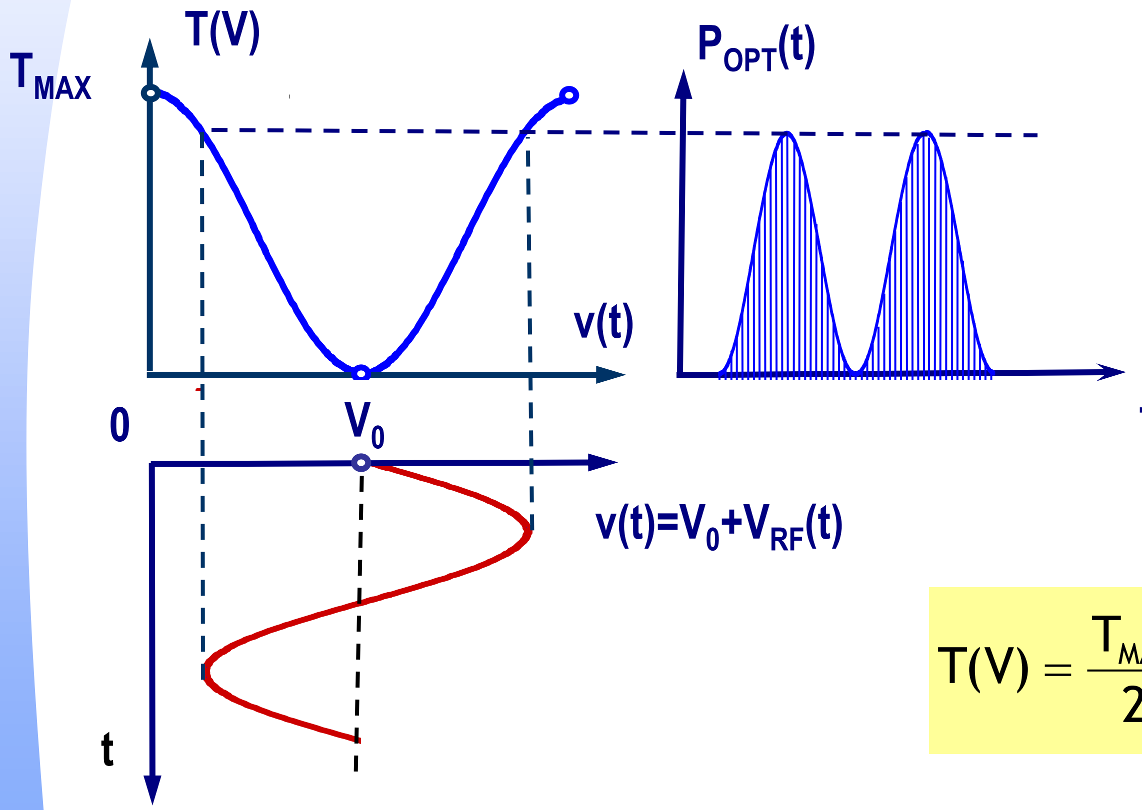


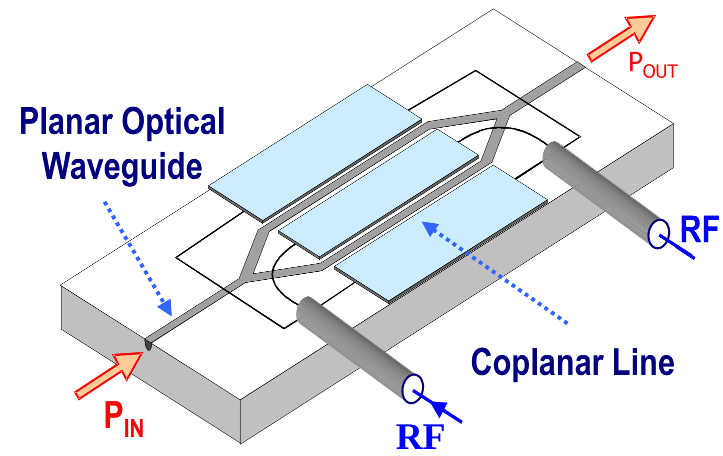
- The slave lasers are synchronized by sidebands after filtration.

The M-Z modulator is used for multiplication of frequency



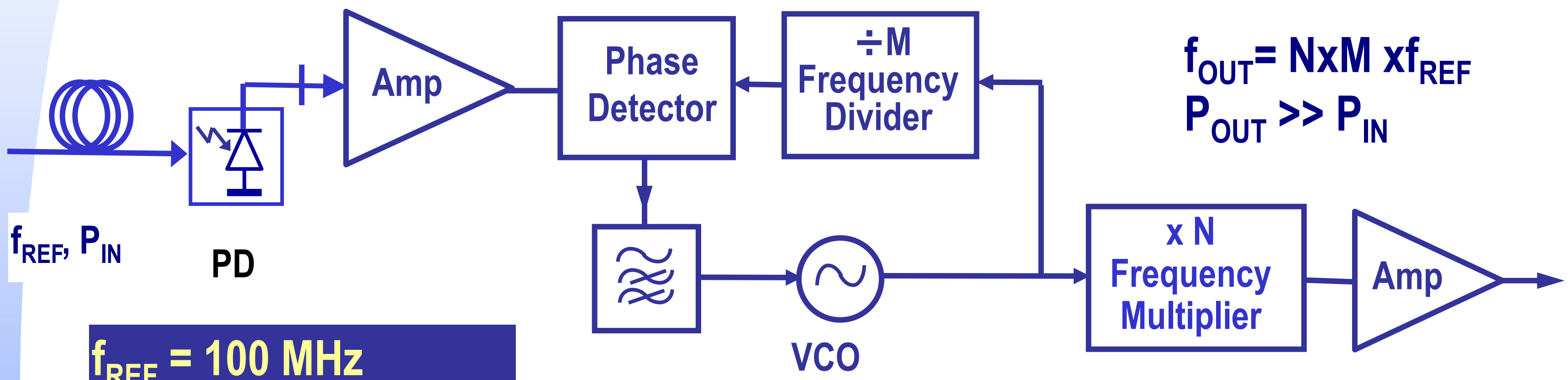
- Mach-Zehnder modulator used for multiplication of frequency





$$T(V) = \frac{T_{MAX}}{2}\left\{1 + \cos\left[\frac{\pi v(t)}{2V_{\pi}}\right]\right\};$$

- It is possible to transmit reference frequency f_{REF} and to control a frequency of VCO by Phase Detector and PLL system.
- With using frequency multiplication process we can obtain every frequency from millimetre-wave region.



f_{REF} = 100 MHz
f_{VCO} = 40x100 = 4 GHz
f_{OUT}= 4x16 = 64 GHz

- Complex and universal circuit for optical controlling of frequency from millimetre-wave region.

5. Conclusions

- In many cases application of the photonic technology to microwave circuits and systems opens new possibility, improves their features and parameters.

- Photonic technology opens new possibilities to transmit the microwave signals, especially in millimeter wave region.

Thank you
for your attention