14. Fundamentals of monolithic microwave integrated circuits and photonic integrated circuits



- 14.1 Monolithic Microwave Integrated Circuits (MMIC)
- 14.2 Photonic integrated circuits (PIC)
 - Arrayed Waveguide Grating (AWG)
 - Mach-Zehnder Interferometer (MZI)
 - DQPSK demodulator

LSI and MMIC









Source: National Radi Astronomy Observatory

Mixer for ALMA telescope (GaAs, 74.3-87.7 GHz)



> Oscillator

- > Amplifier
- Frequency converter
- Transmitter and receiver circuits

Examples of photonic integrated circuit





Arrayed Waveguide Grating (AWG) (K. Sakai, et al., Electron. Lett. Vol. 41, pp.1541-1542 (2005))

Differential Quadrature Phase Shift Keying (DQPSK) demodulator circuit (Courtesy: Prof. Hiroyuki Uenohara, Tokyo Tech.)



Multiplexer/Demultiplexer for lightwave





Grating:

- mature optics
- provides sufficient wavelength resolution good for Dense Wavelength Division Multiplex (DWDM)
- bulky (not suitable for integration)

Arrayed Waveguide Grating (AWG)



Commonly used in photonic integrated circuits for DWDM MUX/DEMUX



https://en.wikipedia.org/wiki/Arrayed_waveguide_grating

path difference ΔL



in-phase condition dependent on a wavelength λ



diffraction angle θ dependent on λ

Arrayed Waveguide Grating (AWG)





path difference $\Delta L \implies (n_s d \sin \theta + n_c \Delta L) k_0$

in-phase condition

Lightwave of wavelength λ focuses at angle θ .

$$(n_s d \sin \theta + n_c \Delta L)k_0 = 2m\pi$$
$$n_s d \sin \theta + n_c \Delta L = m\lambda$$
$$\therefore \sin \theta = \frac{m\lambda - n_c \Delta L}{n_s d}$$

Arrayed Waveguide Grating (AWG)

$$n_{s}d\sin\theta_{1} + n_{c}\Delta L = m\lambda_{1}$$

$$n_{s}d\sin\theta_{2} + n_{c}\Delta L = m\lambda_{2}$$

$$m(\lambda_{1} - \lambda_{2}) = m\Delta\lambda = n_{s}d(\sin\theta_{1} - \sin\theta_{2})$$

$$= n_{s}d(\sin\theta_{1} - \sin\theta_{1}\cos\Delta\theta - \cos\theta_{1}\sin\Delta\theta)$$

$$\approx -n_{s}d\Delta\theta\cos\theta$$

$$\therefore \Delta\lambda = \frac{-n_{s}d\cos\theta}{m}\Delta\theta$$

angular displacement -(lens with focal distance f) --> spatial displacement

$$\Delta x = f\Delta\theta = \frac{-mf}{n_s d\cos\theta}\Delta\lambda$$
$$\therefore \frac{\Delta x}{\Delta\lambda} = \frac{-mf}{n_s d\cos\theta}$$







$$f_e(x) \approx f_o(x) \approx f(x) = f(-x)$$



$$\begin{pmatrix} E_1(x,z) \\ E_2(x,z) \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} E_1(x,0) \\ E_2(x,0) \end{pmatrix}$$

input from port 1

 $\begin{pmatrix} E_1(x,z) \\ E_2(x,z) \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} f(-x) \\ 0 \end{pmatrix} \qquad \begin{array}{c} f_e(x) \approx f_o(x) \approx f(x) = f(-x) \\ E_e = E_o = 1/2 \end{array}$

$$E_{1}(x,z) = T_{11}f(-x) = E_{e}f_{e}(-x)e^{-j\beta_{e}z} + E_{o}f_{o}(-x)e^{-j\beta_{o}z}$$
$$= \frac{f(-x)}{2}\left(e^{-j\beta_{e}z} + e^{-j\beta_{o}z}\right) = \cos\left(\frac{\beta_{e} - \beta_{o}}{2}z\right)e^{-j\frac{\beta_{e} + \beta_{o}}{2}z}f(-x)$$
$$\therefore T_{11} = \cos\left(\frac{\beta_{e} - \beta_{o}}{2}z\right)e^{-j\frac{\beta_{e} + \beta_{o}}{2}z}$$

 $E_{2}(x,z) = T_{21}f(-x) = E_{e}f_{e}(x)e^{-j\beta_{e}z} - E_{o}f_{o}(x)e^{-j\beta_{o}z}$

$$= -j\sin\left(\frac{\beta_e - \beta_o}{2}z\right)e^{-j\frac{\beta_e + \beta_o}{2}z}f(-x)$$

$$\therefore T_{21} = -j\sin\left(\frac{\beta_e - \beta_o}{2}z\right)e^{-j\frac{\beta_e + \beta_o}{2}z}$$



input from port 2

$$\begin{pmatrix}
E_{1}(x,z) \\
E_{2}(x,z)
\end{pmatrix} = \begin{pmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{pmatrix} \begin{pmatrix}
0 \\
f(x)
\end{pmatrix} \quad E_{e} = -E_{o} = 1/2$$

$$E_{1}(x,z) = T_{12}f(x) = E_{e}f_{e}(-x)e^{-j\beta_{e}z} + E_{o}f_{o}(-x)e^{-j\beta_{o}z}$$

$$= \frac{f(-x)}{2}\left(e^{-j\beta_{e}z} - e^{-j\beta_{o}z}\right) = -j\sin\left(\frac{\beta_{e} - \beta_{o}}{2}z\right)e^{-j\frac{\beta_{e} + \beta_{o}}{2}z}f(x)$$

$$\therefore T_{12} = -j\sin\left(\frac{\beta_{e} - \beta_{o}}{2}z\right)e^{-j\frac{\beta_{e} + \beta_{o}}{2}z}$$

$$E_{2}(x,z) = T_{22}f(x) = E_{e}f_{e}(x)e^{-j\beta_{e}z} - E_{o}f_{o}(x)e^{-j\beta_{o}z}$$

$$= \cos\left(\frac{\beta_{e} - \beta_{o}}{2}z\right)e^{-j\frac{\beta_{e} + \beta_{o}}{2}z}f(x)$$

$$\therefore T_{22} = \cos\left(\frac{\beta_{e} - \beta_{o}}{2}z\right)e^{-j\frac{\beta_{e} + \beta_{o}}{2}z}$$

$$\left(T_{11} - T_{21}\right) = \begin{pmatrix}\cos\left(\frac{\beta_{e} - \beta_{o}}{2}z\right) - j\sin\left(\frac{\beta_{e} - \beta_{o}}{2}z\right)\\ - j\sin\left(\frac{\beta_{e} - \beta_{o}}{2}z\right) - \cos\left(\frac{\beta_{e} - \beta_{o}}{2}z\right)\end{pmatrix}e^{-j\frac{\beta_{e} + \beta_{o}}{2}z}$$



coupling coefficient :
$$\kappa = \frac{\beta_e - \beta_o}{2}$$

$$[T] = \begin{pmatrix} \cos \kappa z & -j \sin \kappa z \\ -j \sin \kappa z & \cos \kappa z \end{pmatrix} e^{-j\frac{\beta_e + \beta_o}{2}z}$$

 $\kappa z = \pi / 4$ 50% coupling (3-dB directional coupler)

$$[T] = \begin{pmatrix} \frac{1}{\sqrt{2}} & -j\frac{1}{\sqrt{2}} \\ -j\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} e^{-j\frac{\beta_e + \beta_o}{2}z}$$

Mach-Zehnder Interferometer (MZI)







3dB directional coupler

$$\begin{bmatrix} 0 & 0 & \frac{1}{\sqrt{2}} & -j\frac{1}{\sqrt{2}} \\ 0 & 0 & -j\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -j\frac{1}{\sqrt{2}} & 0 & 0 \\ -j\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \end{bmatrix}$$

Output
$$\square \left[\begin{array}{c} 0 \\ 0 \\ \frac{1}{2} e^{j\varphi_{1}} (1 - e^{j(\varphi_{2} - \varphi_{1})}) \\ \frac{-j}{2} e^{j\varphi_{1}} (1 + e^{j(\varphi_{2} - \varphi_{1})}) \end{array} \right]$$

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Mach-Zehnder Interferometer (MZI)





QPSK signal





Demodulator for DQPSK signals



Pout = out4 - out3 = cost	$\left(\phi_0 + \phi\right)$
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φ ₀	0	π/2	π	3π/2		
MZI-A	1	-1	-1	1		
MZI-B	1	1	-1	-1		
Data	00	10	11	01		
*2 bits data / symbol						

Tokyo Tech

Applications of MZI



When the phase difference is

(a) controlled by an external field:

$$\varphi_2 - \varphi_1 = \begin{cases} 2n\pi \\ (2n-1)\pi \end{cases}$$
 switch / modulator

(b) dependent on frequency :

$$\varphi_2(f) - \varphi_1(f) = \begin{cases} 2n\pi \\ (2n-1)\pi \end{cases}$$
 demultiplexer

(c) dependent on propagation direction :