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Principle of Coherence Optical Systems-Current Applications and Future Challenges

Arun Agarwal[1,*], Kabita Agarwal[2], Gourav Misra[3], Subrat Kumar Panda[4]

[1]Department of ECE, Institute of Technical Education & Research (ITER), Siksha 'O' Anusandhan Deemed to be University, Khandagiri Square, Bhubaneswar-751030, Odisha, India
[2]Department of Electronics and Instrumentation Engineering, College of Engineering & Technology (CET), Ghatikia, Kalinga Nagar, Bhubaneswar-751003, Odisha, India
[4]School of Electronic Engineering, Dublin City University, Glasnevin, Dublin 9, Ireland
[4]Department of ECE, Gandhi Institute For Technology (GIFT), Gramadiha, PO-Gangapada, Bhubaneswar-752054, Odisha, India
*Corresponding author: arunagrawal@soa.ac.in

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Abstract This paper reviews the concept of coherent optical systems as future digital optical communication systems having capacity of achieving 100Gbps speed. While the transmission capacity increases in wavelength-division multiplexed (WDM) system, coherent technologies have been in large interest in recent years. The interest lies in finding methods of increasing the bandwidth demand with multilevel modulation formats based on coherent technologies. We also discuss about requirements and challenges in implementation of respective digital receivers and associated signal processing.

Keywords: *optical systems, WDM, coherent, bandwidth, signal processing, digital receivers*

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1. Introduction

In the 1980s Coherent optical fiber communications were studied extensively mainly because high sensitivity of coherent receivers could be used for a higher transmission distance; however, due to the rapid progress in high-capacity wavelength-division multiplexed (WDM) systems using erbium-doped fiber amplifiers (EDFAs) their research and development have been interrupted for nearly 20 years behind.

In 2005, there was a large interest in the topic because of the digital coherent receivers which does not depend upon any complicated process rather uses variety of spectrally efficient modulation formats such as M-ary phase shift keying (PSK) and quadrature amplitude modulation (QAM). By this process the phase information are not being lost and different offset like chromatic dispersion and polarization-mode dispersion can be compensated. Taking these aspects into consideration the coherent optical is being in research in the field of optical communication systems.

2. The New Coherence Optical Communication Transmission

2.1. Digital Communication

Digital modulation is the mapping of digital sequence i.e. the binary data in analog form or signal. In digital modulation scheme a block of k bit data's are mapped into one modulation level M, where $M = 2^k$ to generate a signal $S_m(t)$, where m lies between $1 \le m \le 2^k$ .In this way it is possible to increase the transmitted bit rate by transmitting k number of bits of information in every T_s sec.

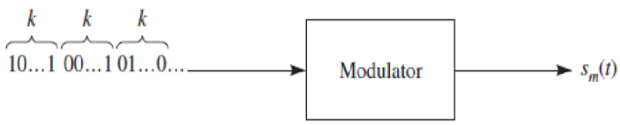

Figure 1. Generation of $S_m(t)$

There are different modulation schemes in which $S_m(t)$ can be used are pulse amplitude modulation (PAM), phase shift keying (PSK), quadrature shift keying (QAM).

In PAM the amplitude of the signal is varied. Suppose a signal $S_m(t)$ be like,

$$S_m(t) = A_m \cos(2\pi f_c t)$$

Where, $A_m = 0,1,2 \ldots (M-1)$.

In PSK the phase of the signal is varied. Suppose a signal $S_m(t)$ be like,

$$S_m(t) = g(t)\cos\left(2\pi f_c t + \frac{2\pi}{M}(m-1)\right).$$

In QAM both the amplitude and phase of the signal are varied. The signal $S_m(t)$ be like,

$$S_m(t) = I_m g(t)\cos(2\pi f_c t) + Q_m g(t)\sin(2\pi f_c t)$$

Where, $I_m, Q_m = \pm 1, \pm 3, \ldots \ldots (\pm M - 1)$.

2.2. Phase Modulation

Phase modulators are used to achieve Optical amplitude modulation (AM) in a Mach–Zehnder configuration which are driven in a push–pull mode of operation. Optical IQ modulation can be consists of a push–pull type MZM in parallel, with one of the MZM given a $\pi/2$ phase shift.

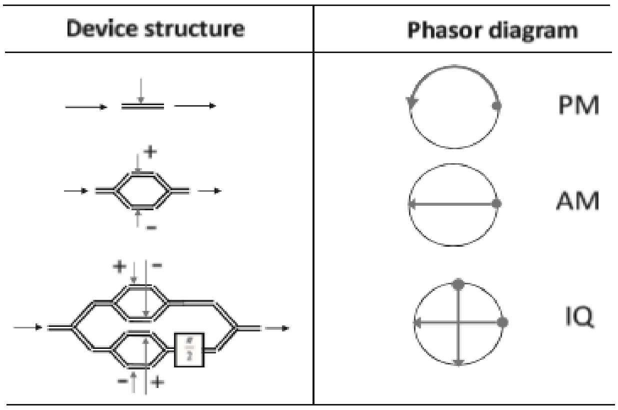

Figure 2. Device structure and the phasor diagram comparison among phase modulation, amplitude modulation, and IQ modulation.

Phase modulation depends on the wavelength λ, electrode length (interaction length) l_{el}, and the change of the effective refractive index Δn_{eff}. Considering only the Pockels effect, the change of the refractive index can be assumed to be linear w.r.t. the applied external voltage u(t):

$$\varnothing_{PM}(t) = \frac{2\pi}{\lambda} \Delta n_{eff}(t).l_{el} \sim u(t).$$

Transfer function: $E_{out}(t) = E_{in}(t) e^{i\frac{u(t)\pi}{v_\pi}}$.

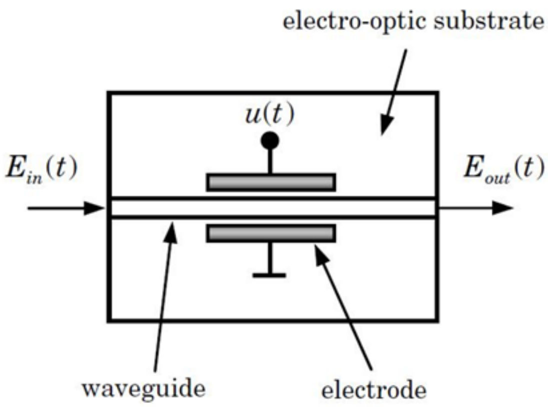

Figure 3. Device structure of phase modulation

2.3. Mach-zehender Modulation

When two phase modulators are placed parallel using an interferometric structure a mach zehender is formed. In a MZM the incoming light is split into two branches, with different phase shifts applies to each path, and then they recombined. The output of MZM is a result of interference, ranging from constructive (the phase of the light in each branch is the same) to destructive (the phase in each branch differs by π).

Transfer function:

$$E_{out}(t) = E_{in}(t)(e^{i\varnothing_1(t)} + e^{i\varnothing_2(t)})$$

$$\varnothing_1(t) = \frac{u_1(t)\pi}{v_\pi}$$

$$\varnothing_2(t) = \frac{u_2(t)\pi}{v_\pi}$$

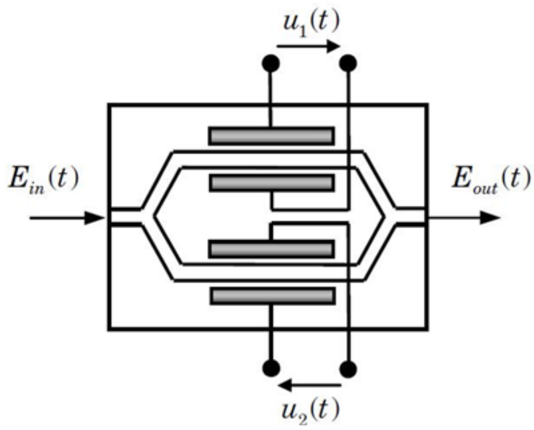

Figure 4. Device structure of MZM

When MZM is operating in push-push condition, $u_1(t) = u_2(t)$.
When MZM is operating in push-pull condition, $u_1(t) = -u_2(t)$.

In push-push condition the MZM works as a pure phase modulation system and in push-pull as pure amplitude modulation system.

In push-pull condition, $u_1(t) = -u_2(t) = \frac{u(t)}{2}$.

In push-pull operation the field (E) and the power (P) transfer function of the MZM is,

$$E_{out}(t) = E_{in}(t)\cos\left(\frac{\Delta\varphi_{MZM}(t)}{2}\right) = E_{in}(t)\cos\left(\frac{u(t)\pi}{2v_\pi}\right)$$

$$\frac{P_{out}(t)}{P_{in}(t)} = \frac{1}{2} + \frac{1}{2}\cos\left(\Delta\varphi_{MZM}(t)\right) = \frac{1}{2} + \frac{1}{2}\cos\left(\frac{u(t)\pi}{v_\pi}\right)$$

$$\Delta\varphi_{MZM}(t) = \frac{u(t)\pi}{v_\pi}.$$

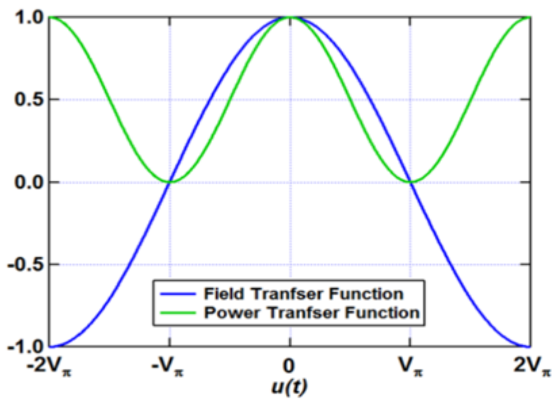

Figure 5. Field and power transfer function

When MZM, bias voltage is at quadrature point i.e. $V_{bias} = -\frac{v_\pi}{2}$ and modulate with a inpute voltage swing of v_π peak-to-peak. In this condition the MZM acts as a pure amplitude modulation technique (example: on-off keying).

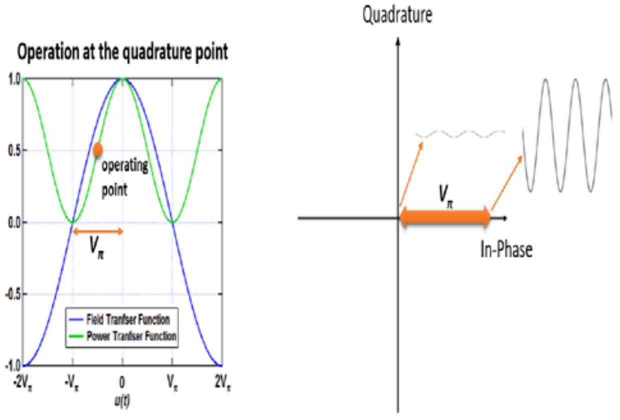

Figure 6. Operation at Quadrature point

When MZM, bias voltage is at minimum transmission point i.e. $V_{bias} = -v_\pi$ and modulate with an input voltage swing of $2v_\pi$ peak-to-peak, in addition to amplitude modulation, a phase change of π occurs every time the input, u(t), crosses the minimum transmission point (example: BPSK).

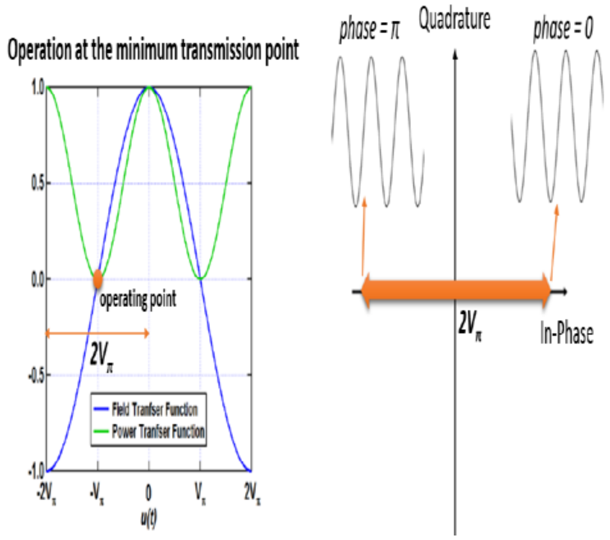

Figure 7. Operation at minimum point

2.4. Optical IQ Modulator

Here MZMs working in push-pull condition are placed parallel to one another with a $\frac{\pi}{2}$ phase shift to the second MZM.

The transfer function of dual drive MZM is:

$$\frac{E_{out}(t)}{E_{in}(t)} = \cos\frac{E_{out}(t)}{E_{in}(t)}$$

$$= \cos\left(\frac{\Delta\varphi_I(t)}{2}\right) + \cos\left(\frac{\Delta\varphi_Q(t)}{2}\right).e^{i\frac{\pi}{2}}$$

$$E_{out}(t) = E_{in}(t)\left[\cos\left(\frac{\Delta\varphi_I(t)}{2}\right) + i\cos\left(\frac{\Delta\varphi_Q(t)}{2}\right)\right]$$

$$\Delta\varphi_I(t) = \frac{(V_I + V_{DC})\pi}{v_\pi}$$

$$\Delta\varphi_Q(t) = \frac{(V_Q + V_{DC})\pi}{v_\pi}.$$

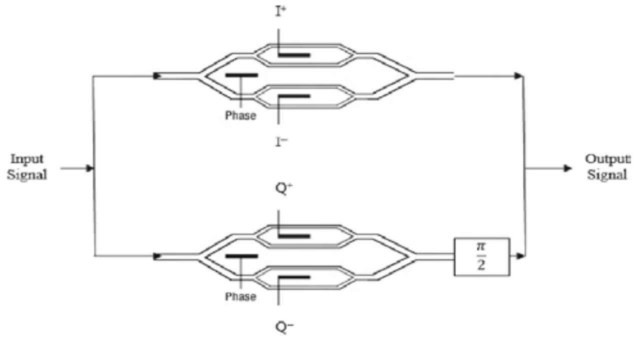

Figure 8. MZM IQ Modulator

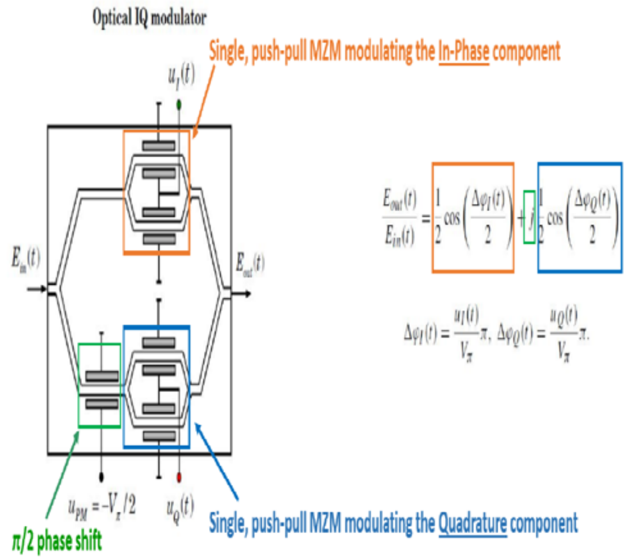

Figure 9. Dual-Nested IQ (In-Phase, Quadrature) Mach-Zehnder Modulator (with each MZM biased at minimum transmission point)

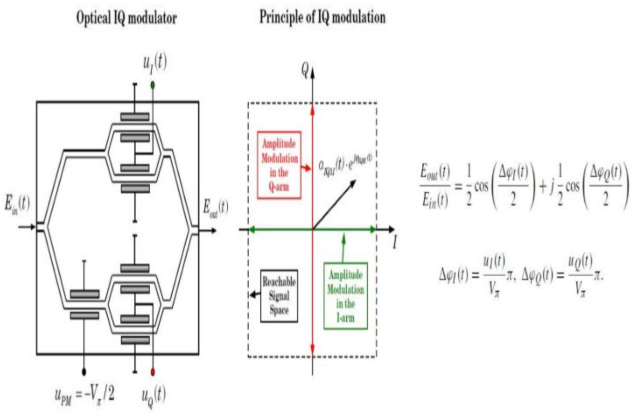

Figure 10. Dual-Nested IQ (In-Phase, Quadrature) MZM(with each MZM biased at minimum transmission point) and principle behind it.

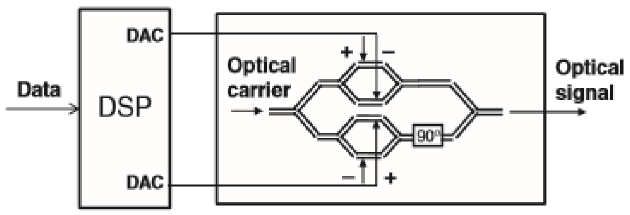

Figure 11. DSP based optical transmitter

3. Direct Detection Scheme

Through direct detection at the optical receiver the digital information is recovered in the intensity modulated format by help of a photodiode that helps in converting the power of the optical carrier into electrical current. The photocurrent that is produced is directly proportional to the square of the signal amplitude.

$$I_{ID} \propto E_S \cdot E_S' = \left(A_S e^{j(\omega_s t+\varphi)}\right)\cdot\left(A_S e^{-j(\omega_s t+\varphi)}\right) = A_S^2$$

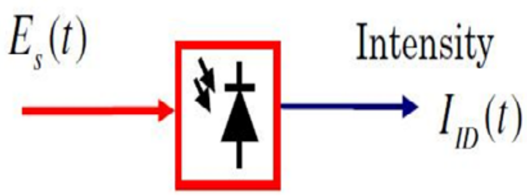

Figure 12. Photodiode working

3.1. IQ Demodulation Formats

An IQ demodulator mixes the received modulated carrier with a Continuous Wave (CW) Local Oscillator (LO), and a 90-degree shifted version of the LO the signal is down-converted from the carrier frequency down to baseband, and the in-phase and quadrature components can be recovered. Its functionality is to essentially obtain the complex envelope (and therefore, the data) of a modulated carrier.

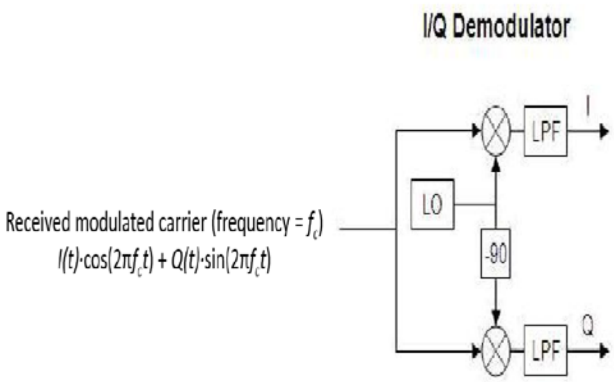

Figure 13. IQ demodulator

3.2. 90° Hybrid

In an optical demodulator, the used IQ demodulator is a 90 degree hybrid. It is used to mix the received signal with the local oscillator signal and also the shifted local oscillator signal.

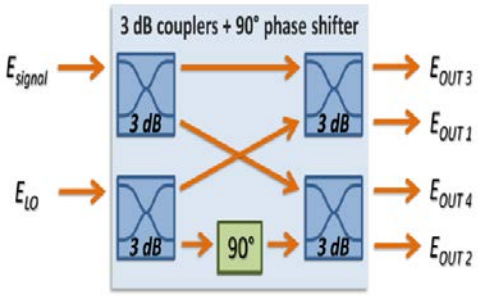

Figure 14. 3dB coupler with 90 degree phase shift

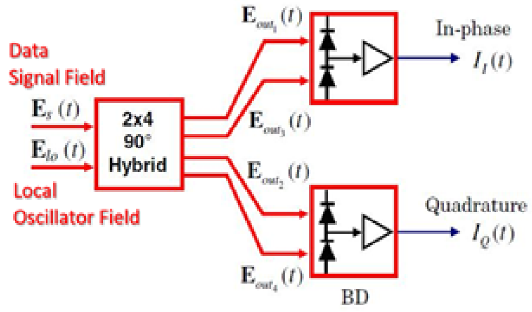

Figure 15. Coherence receiver

$$E_1(t) = \frac{1}{2}\left(E_s(t) + E_{LO2}(t)\right)$$

$$E_2(t) = \frac{1}{2}\left(E_s(t) - E_{LO2}(t)\right)$$

$$E_3(t) = \frac{1}{2}\left(E_s(t) + iE_{LO2}(t)\right)$$

$$E_4(t) = \frac{1}{2}\left(E_s(t) - i\,E_{LO2}(t)\right)$$

$$I_I(t) = R\sqrt{P_s P_{LO2}}\cos\left(\theta_s(t) - \theta_{LO2}(t)\right)$$

$$I_Q(t) = R\sqrt{P_s P_{LO2}}\sin\left(\theta_s(t) - \theta_{LO2}(t)\right)$$

$$I(t) = I_I(t) + iI_Q(t)$$

$$I(t) = R\sqrt{P_s P_{LO2}}\,e^{i\left(\theta_s(t) - \theta_{LO2}(t)\right)}$$

3.3. Polarization Diversity Coherent Receiver

Two coherent receivers are employed to detect the two orthogonal polarizations of the received signal (the polarizations are separated using a Polarization Beam Splitter).

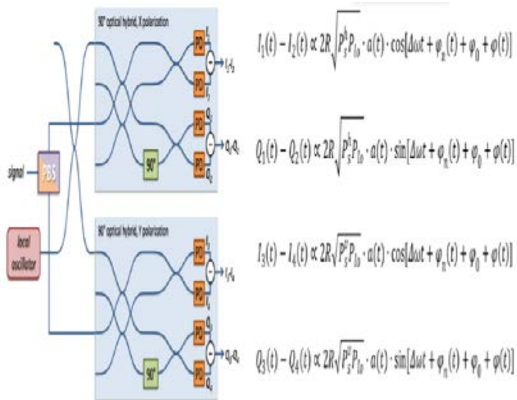

Figure 16. PD coherent receiver

4. DSP Advantages

1. Recent developments in high-speed ADCs and ASICs have enabled the use of real-time DSP algorithms to demodulate Gbit/s coherent optical signals.
2. By DSP processing it is possible to compensate for the “incoherence” (frequency offset and phase noise) of the Tx and LO lasers.
3. Advanced RF/wireless comms concepts finally applicable for ultra-high speed optical communications.
4. State-of-the-art: 100 Gbits/s optical transceivers are a commercial reality and deployed by major telecom operators today (DP-QPSK at 25 Gbaud symbol rate).
5. DSP can also be used to compensate for link impairments:
   i. Chromatic Dispersion (CD)
   ii. Fiber nonlinearities
   iii. Bandwidth limitations
6. Higher rates and longer transmission distances
7. Universal transceivers using the same hardware in all parts of the network; rate and format is determined by the software.
8. More transparent and upgradable networks Lower cost

5. Conclusion and Future Work

The progress in coherence optical is very rapid in past years. In the future years it can use in

1. long distance communications,
2. high speed coherence receiver can be
3. tunneble local oscillator with narrow line-width
4. more flexible DSP with high error correction rate
5. Hybrid integration of planar light-wave circuits (PLCs) for phase and polarization diversities, double balanced photodiodes, and a local oscillator is an important technical task, which enables cost reduction of the coherent receiver and improves system stability.

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