Direct Detection

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Coherent Heterodyne Detection

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Direct Detection :- The lightwave systems based on a simple digital modulation scheme in which an electrical bit stream modulates the intensity of an optical carrier inside the optical transmitter and the optical signal transmitted through the fiber link is incident directly on an optical receiver, which converts it to the original digital signal in the electrical domain. Such a scheme is referred to as intensity modulation with direct detection (IM/DD).

Photodetectors produce currents proportional to the incident optic power. Detectors respond to fluctuations in the light intensity, a characteristic independent of the light's phase or frequency. Thus optic detectors do not reproduce variations in the frequency or phase of the oscillating lightwave. Because of this, frequency modulation of an optic source is ineffective for communication via the direct detection methods.

$$\text{Photo current } (i) = \frac{\eta e P}{hf} = \frac{\eta e \lambda P}{hc} \qquad \text{—(1)}$$

hf is the energy per photon, η is the quantum efficiency $\left(= \frac{\text{no. of emitted } e^-}{\text{no. of incident photon}}\right)$

e is the electron carries a charge, P is optic input power.

The responsivity, ρ, is the ratio of the output current of the detector to its optic input power i.e.

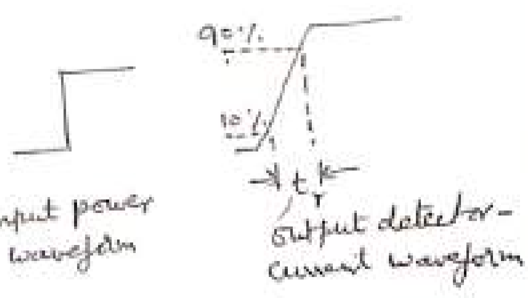
$$\rho = \frac{i}{P} \ \text{A/W} \quad ; \quad \text{A means amperes, W means watt.} \qquad \text{—(2)}$$

Using eqn (1) we get $\quad \rho = \frac{i}{P} = \frac{\eta e}{hf} = \frac{\eta e \lambda}{hc}$

The output voltage is $\quad V = R_L i = R_L \cdot \frac{\eta e P}{hf} = \rho R_L P \qquad$ —(3)

Eqn (1) shows that the detected current is directly proportional to the optic power.

The rise time, t_r, is the time for the detector output current to change from 10 to 90% of its final value when the optic-input power variation is a step. Detector rise-time is illustrated in figure.



Heterodyne Detection : Frequency modulation of an optic source is ineffective for communication via the direct detection methods. However, optic frequency-modulation systems are possible by using heterodyne detection, this is also called coherent detection.

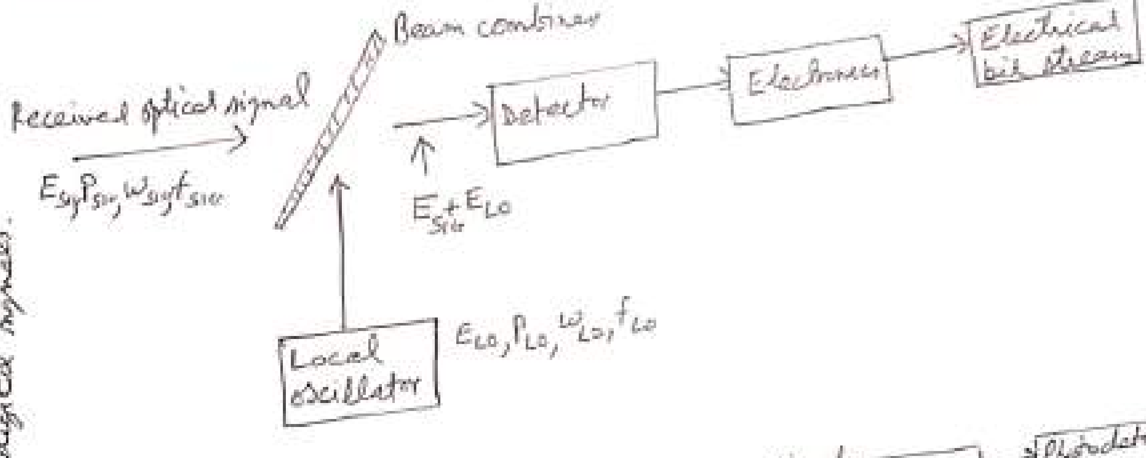
Many alternative scheme, well known in the context of radio and microwave communication systems, transmit information by modulating the frequency or the phase of the optical carrier and detect the transmitted signal by using homodyne or heterodyne detection techniques. Since phase coherence of the optical carrier plays an important role in the implementation of such schemes, such optical communication systems are called coherent lightwave systems. The motivation behind using the coherent communication techniques is two-fold.

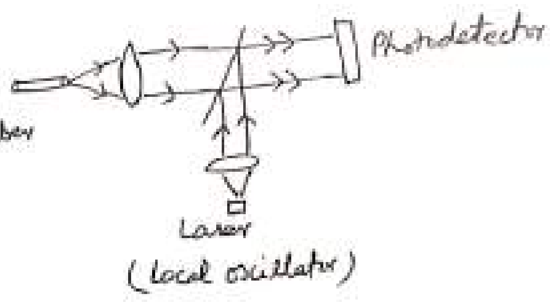
(1) The receiver sensitivity can be improved by upto 20dB compared with that of Direct detection systems.

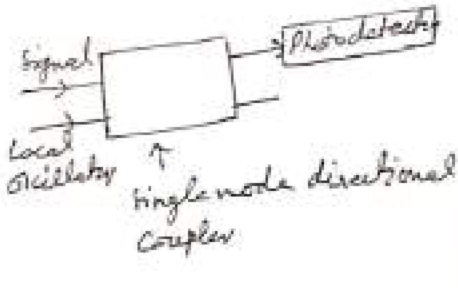
(2) The use of ~~cohent~~ coherent detection may allow a more efficient use of fiber bandwidth by increasing the spectral efficiency of WDM systems.

Heterodyne receivers are also effective for detecting intensity-modulated digital signals.

Basic Concepts :- The basic idea behind coherent detection consists of combining the optical signal coherently with a continuous-wave optical field before it falls on the photodetector. The continuous-wave (CW) field is generated locally at the receiver using a narrow-linewidth laser, called the local oscillator (LO), a term borrowed from the radio and microwave literature. Hetrodyne detection depends upon the interference between local oscillator and signal light beam. They will not interfere unless they are identically polarised. Thus a source of linear polarization is needed. * The process of heterodyne detection is shown in figures.







* The heterodyne detector convert phase changes in the optic carrier to phase changes in the optic intensity. This variations are reproduced in the detected current waveform, making possible the reception and demodulation of frequency-modulated optic carriers. Thus it also effective for detecting intensity-modulated digital signals.

A simple analysis shows how the heterodyne scheme permits detection of the modulation. The electric fields of the transmitted signal and the local oscillator beams are given by

$$E_{SIG} = E_S \cos(\omega_s t + \phi) \quad \text{——(1)}$$

$$E_{LO} = E_{LO} \cos(\omega_{LO} t) \quad \text{——(2)}$$

Where ω_s is the carrier frequency, E_s is the amplitude, ϕ is the phase, ω_{LO} is the local oscillator frequency, E_{LO} is the amplitude.
The scalar notation is used for both E_s and E_{LO} after assuming that the two fields are identically polarized.
x [Since a photodetector responds to the optical intensity, the optical power incident at the photodetector is given by] or The detected current is proportional to the intensity I (the square of the total electric field) of the incident light beam.
Thus

$$I = (E_{SIG} + E_{LO})^2 \quad \text{——(3)}$$

substituting Eqs(1) and (2) into eq(3) we get.

Intensity,

$$I = \left[E_s \cos(\omega_s t + \phi) + E_{LO} \cos(\omega_{LO} t)\right]^2$$

$$= E_s^2 \cos^2(\omega_s t + \phi) + E_{LO}^2 \cos^2(\omega_{LO} t) + 2 E_s E_{LO} \cos(\omega_s t + \phi) \cos(\omega_{LO} t)$$

$$= \frac{E_s^2}{2}\left[1 + \cos 2(\omega_s t + \phi)\right] + \frac{E_{LO}^2}{2}\left[1 + \cos 2(\omega_{LO} t)\right]$$
$$+ E_s E_{LO}\left[\cos\{(\omega_s + \omega_{LO}) t + \phi\} + \cos\{(\omega_s - \omega_{LO}) t + \phi\}\right]$$

$$= \frac{E_s^2}{2} + \frac{E_s^2}{2} \cos 2(\omega_s t + \phi) + \frac{E_{LO}^2}{2} + \frac{E_{LO}^2}{2} \cos 2(\omega_{LO} t)$$
$$+ E_s E_{LO}\left[\cos\{(\omega_s + \omega_{LO}) t + \phi\} + \cos\{(\omega_s - \omega_{LO}) t + \phi\}\right] \quad \text{——(4)}$$

The term II, IV and V oscillate near $2\omega_s$. This frequency is much greater than the frequency response of the detector, so that all intensity components near this frequency are eliminated from the receiver.

$$I = \frac{E_s^2}{2} + \frac{E_{LO}^2}{2} + E_s E_{LO} \cos\{(\omega_s - \omega_{LO}) t + \phi\} \quad \text{——(5)}$$

(beat frequency)

Let $\omega_{IF} = \omega_s - \omega_{LO}$, ω_{IF} is known as intermediate frequency and its value normally in the radio frequency range. It may be a few tens or hundreds of megahertz (MHz). A homodyne detection system results if there is no offset, i.e. if $\omega_{IF} = 0$ or $\omega_s = \omega_{LO}$.

Eq.(5) becomes

$$I = \frac{E_s^2}{2} + \frac{E_{LO}^2}{2} + E_s E_{LO} \cos(\omega_{IF} t + \phi) \quad \text{——(7)}$$

The corresponding optical power (which is proportional to the intensity).

$$\text{photocurrent } (i) = \frac{\eta e P}{hf} \propto \text{Intensity} \quad \text{——— (8)}$$

Thus

optical power, $$P = P_s + P_{LO} + 2\sqrt{P_s P_{LO}} \cos(\omega_{IF} t + \phi) \quad \text{——— (9)}$$

where P_s and P_{LO} are the powers in the signal beam and local oscillator respectively.

Now the photocurrent corresponding to power is given as, using eqn (8),

$$i(t) = \frac{\eta e}{hf}(P_s + P_{LO}) + \frac{2\eta e}{hf}\sqrt{P_s P_{LO}} \cos(\omega_{IF} t + \phi) \quad \text{——— (10)}$$

The current, i, includes a dc term

$$i_{dc} = \frac{\eta e}{hf}(P_s + P_{LO}) \quad \text{——— (11)}$$

and one at the ω_{IF} frequency

$$i_{IF} = \frac{2\eta e}{hf}\sqrt{P_s P_{LO}} \cos(\omega_{IF} t + \phi) \quad \text{——— (12)}$$
$$= 2\rho\sqrt{P_s P_{LO}} \cos(\omega_{IF} t + \phi)$$

The dc current is generally filtered out and the IF current is amplified. Notice that the information-bearing IF current increases with local oscillator power. In effect, the LO acts as a signal amplifier, increasing the sensitivity of the receiver.

Variation in detector current varies due to beat frequency or intermediate frequency in such a way that the amplitude of signal has been amplified.

Now

$$i(t) \propto \sqrt{P_s P_{LO}}$$
$$\propto E_s \quad ; P_{LO} \text{ is constant.} \quad \text{——— (13)}$$

It means that detector current is proportional to the amplitude of electric field of signal.

Most fibers do not maintain a wave's state of polarization, during travel, the direction of polarization could rotate, and then the linear state would change to some other polarization. Also, environmental factors (such as small temperature shifts and vibrations) can cause random variations in the state of polarization. Specially constructed polarization-maintaining single-mode fibers are required for practical heterodyne systems.

The frequency offset between the LO and the transmitter can be finely tuned by use of the temperature-dependent wavelength property of laser diodes. Two identical diodes, operated at slightly different temperatures will oscillate at different frequencies. Once set, the laser temperature must be maintained within a very small fraction of a degree celsius to keep the IF frequency from changing too much.

Advantages of coherent detection over direct detection :- Heterodyne detection has several attractions :-

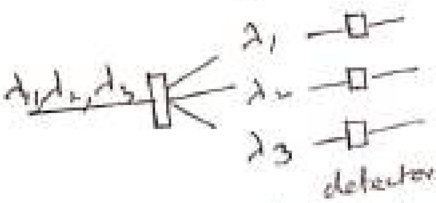
1. Receiver Sensitivity increases :- If heterodyne detection is used at the receiver end, with the detector even a very low power will result in very good output i.e. resultant output gets amplified and sensitivity of receiver increases.
2. Longer links can be designed if repeater is installed. Thus link length increase.
3. Bandwidth increases for the same optical power, almost double bandwidth signal can be detected in comparison with direct detection.
4. Frequency division multiplexing can be achieved.
5. Filtering or Demodulation : separation of channels can be done as in electronic domain (where electronic filters are used), beat or intermediate frequency. $\omega_{IF} = \omega_S - \omega_{LO} = 2\pi f_I$, this lies in Radio frequency or μW, which is small in comparison to optical frequency
6. More channels can be transmitted
7. This techniques gives rise to OFDM.

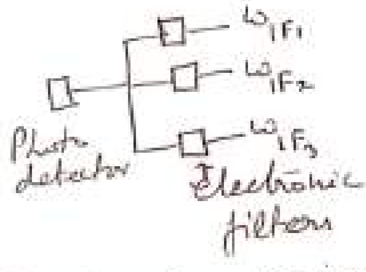
Disadvantages of Heterodyne techniques :-

1. Single mode laser diodes are used as the source of local oscillator, so circuitry is a bit complex and costly as well.
2. Efficient alignment of light sources is required which is indeed a tough job.
3. There should be no chirping (fluctuations) in the laser source, which is slightly difficult.
4. State of polarisation of signal must be same as the state of polarisation of local oscillator, so again optical alignment is difficult.

Comparison between Direct detection and Heterodyne detection :-

Direct Detection	Heterodyne Detection
(1) Using this technique less channels can be transmitted (≈20 channels within 100nm range) as in WDM	(1) More channels can be transmitted (≈ 2000 channels within 100nm range) as in OFDM (optical frequency division multiplexing)
(2) For the same optical power bandwidth is less	(2) Bandwidth is more (double the bandwidth as in direct detection)
(3) Link length is small	(3) Link length is comparitely large than direct detection.
(4) Circuity is less complicated and hence cost is less	(4) Circuit is quite complex as a local oscillator is used so cost is high.
(5) Demultiplexing is done in optical domain before photodetection	(5) Demultiplexing is done in electronic domain after photodetection
(6) Direct detection techniques is used	(6) Heterodyne or indirect detection techniques is used.





Principle on which coherent heterodyne detection works :- The principle of this detection technique is to provide gain to incoming optical signal by mixing it with a locally generated continous wave (CW) optical field. When any two frequencies ω_1 and ω_2 are combined, the resultant is the waves with frequencies $2\omega_1$, $2\omega_2$ and $\omega_1 \pm \omega_2$.

For coherent light wave, all other frequencies except $\omega_1 - \omega_2$ are filtered out at the receiver end) The device which is used ~~creating~~ creating CW signal is a narrow line-width laser called local oscillator.

As a result of this mixing procedure the dominant noise in the receiver is the shot noise coming from local oscillator, receiver can achieve a shot noise limited sensitivity.

Also, it becomes quite difficult to detect the weak signals at the detector end, thus they are mixed with local oscillators waves so that weak signals are amplified and hence detected.

Let $\omega_s = 2\pi f_s$ be weak signal frequency and $\omega_{LO} = 2\pi f_{LO}$ be LO frequency, difference frequency is $(\omega_s - \omega_{LO})$ contains all the information about incoming wave. This difference frequency is called Beat frequency or intermediate frequency (ω_{IF}).

This technique gives rise to OFDM.

* Shot noise is a manifestation of the fact that an electric current consists of a stream of electrons that are generated at random times.