STUDIES ON OPTICAL COMPONENTS AND RADIO OVER FIBRE SYSTEMS

THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF TECHNOLOGY
IN
Electronics and Communication ENGINEERING

By

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DEPARTMENT OF Electronics and communication ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA, ORISSA-769008
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National Institute of Technology
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CERTIFICATE

This is to certify that the thesis entitled **"STUDIES ON OPTICAL COMPONENTS AND RADIO OVER FIBRE SYSTEMS"** submitted by **Ankush Kumar, Roll no-10509029** in partial fulfillment of the requirements for the award of Bachelor of Technology degree in Electronics and communication Engineering at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

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.

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Ankush Kumar

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ABSTRACT

In the modern era good communication systems are the need of the hour. This project includes the study of optical components and Radio over Fibre systems. Various Optical components are used in optical systems and those optical components have different characteristics. Various optical components have been studied in this project and in addition to that there is a study of components using S-matrix. The use of S-matrix in analyising the directional coupler. Optical networks can be analysed with the same methods as microwave networks in theory of microwave networks, components are generally represented by complex scattering parameters which form the S- matrix. we adopted this formalism to fibre optic coupler used in optical network taking the polarization dependence into account. There is the study of Fabry- perot filter in which the study of free spectral range (FSR) and the Transfer function was determined through Matlab simulation. The results thus obtained are studied.

For the future provisions of broadband, multimedia the radio over fibre systems are a good alternative. RoF systems are used basically because of their low loss and extremely wide bandwidth and robustness. Radio over fibre can use millimeter waves and serve as a high speed wireless local or personal area network. In this project various parts of the Radio over fibre systems are studied, The power spectrum measurements of a millimeter wave Radio over Fibre under different single mode fibre length is done with a Matlab simulation it is found that the fading occurs at some values of length of fibre in the power spectrum.

In radio over fibre systems the two subcarrier modulations (SCMs) i.e., single sideband and tandem single sideband have been widely used both SSB and TSSB SCMs can be obtained by using optical mach Zehnder modulator. In this project we investigate the impact of the impact of the harmonic distortion and inter modulation distortion in RoF systems for one wavelength carrying two radio frequency signals with either SSB or TSSB SCM. It is found that non linear distortion can be reduced when the frequency difference ~ 1 GHz. It was found that non linear distortion strongly depends on the modulation index. The source of these results was a mat lab simulation and calculations. For the different values of the signal frequencies the NSR was calculated.

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INTRODUCTION

1.1 OPTICAL COMMUNICATION

Optical communication may be defined as the form of communication that uses light as the transmission medium. An optical communication[32] system has many parts like a transmitter, which encodes a message into an optical signal, it also comprises of a channel, which carries the signal to its destination, and a receiver, which reproduces the message from the received optical signal.

FORMS OF OPTICAL COMMUNICATION

In the old times, Techniques [4], such as semaphore lines, ship flags, smoke signals, and beacon fires were used as optical communication early forms

There is a type of optical communication in which a mirror is used to reflect sunlight to a distant observer. By moving the mirror the distant observer sees flashes of light that can be used to send a prearranged signaling code. It's called as heliograph.

Many mariners used Distress flares in emergencies, while lighthouses and navigation lights are used to communicate navigation hazards.

Optical fibre is the most common medium for modern digital optical communication.

Free-space optical communication is also used today in a variety of applications.

OPTICAL FIBRE COMMUNICATION

The most common type of channel for optical communications is optical fibre, however, there are different types of optical waveguides used in communication systems, The transmitters in optical fibre links are generally light-emitting diodes (LEDs) or laser diodes. Infrared light, rather than visible light is used more commonly, The reason for using the same is because optical fibres transmit infrared wavelengths with less attenuation and dispersion. The signal encoding is typically simple intensity modulation, although optical phase and frequency modulation have been tested in the lab. The need for periodic signal regeneration was largely superseded by the introduction of the erbium-doped fibre amplifier, which amplifies the signal and extended link distances at significantly lower cost.

FREE SPACE OPTICAL COMMUNICATION

Free Space Optics (FSO) systems are point to point communication systems that can function over distances of several kilometers as long as there is a clear line of sight between the source and the destination, and the optical receiver can reliably decode the transmitted information.

1.2 OPTICAL FIBRE

An optical fibre is a glass or plastic fibre that carries light along its length[32].the science dealing with applied science and engineering concerned with the design and application of optical fibres is called as Fibre optics. Optical fibres are widely used in fibre-optic communications, which permits transmission over longer distances and at higher bandwidths (data rates) than other forms of communications. The signals travel along the fibres with less loss, and they are also immune to electromagnetic interference that’s why fibres are used in place of metal wires. Fibres are also used for illumination, and are wrapped in bundles so they can be used to carry images, thus allowing viewing in tight spaces. Specially designed fibres are used for a variety of other applications, including sensors and fibre lasers.

Light is kept in the core of the optical fibre by total internal reflection. This causes the fibre to act as a waveguide. There are two types of Fibres. Fibres which support many propagation paths or transverse modes are called multi-mode fibres (MMF), while those which can only support a single mode are called single-mode fibres (SMF). Multi-mode fibres generally have a larger core diameter, and are used for short-distance communication links and for applications where high power must be transmitted. Single-mode fibres are used for most communication links longer than 550 metres.

Joining lengths of optical fibre is more complex than joining electrical wire or cable. The ends of the fibres must be carefully cleaved, and then spliced together either mechanically or by fusing them together with an electric arc. Special connectors are used to make removable connections.

FIBRE USE IN COMMUNICATION

In 1880, only four years after his invention of the telephone [58], Alexander Graham Bell made a device called photo-phone to use light for the transmission of speech. It was a tube with a flexible mirror at its end. He spoke down the tube and the sound vibrated the mirror. The modulated light was detected by a photocell placed at a distance of 200m or so. After the invention of the ruby laser in 1960, the direct use of light for communication was reinvestigated. However, there was a need of a specific data medium for the systems.

It was an interesting idea and in 1983 it was used to send a message, by Morse code, over a distance of 240 km (150 miles) between two mountaintops. Many researches were done for the development of an optic fibre to carry the light over long distances. The early results were disappointing. The losses were such that the light power was halved every three meters along the route. This would reduce the power by a factor of a million over only 60 meters (200 feet). Obviously this would rule out long distance communications even when using a powerful laser. Then there was usage of a silica glass with losses comparable with the best copper cables. The glass used for optic fibre is unbelievably clear. We occasionally use plastic for optic fibre but its losses are still impossibly high for long distance communications, but for short links of a few tens of meters it is satisfactory and simple to use. It is finding increasing applications in hi-fi systems, And in automobile and other control circuitry. On the other hand, a fibre optic system using a glass fibre is certainly capable of carrying light over long distances. By converting an input signal into short flashes of light, the optic fibre is able to carry complex information over distances of more than a hundred kilometers without additional amplification. This is at least fifty times better than the distances attainable using the best copper coaxial cables. The system is basically very simple: a signal is used to modulate, the light output of a suitable source – usually a laser or an LED (light emitting diode). The flashes of light travel along the fibre and, at the far end, are converted to an electrical signal by means of a photo-electric cell. Thus the original input signal is recovered

MOTIVATIONS FOR USING OPTICAL FIBRE SYSTEMS

The motivation for developing optical fibre communication systems started when laser was invented in the early 1960s. The further studies of this device encouraged researchers to examine the optical spectrum as an extension of the radio and microwave spectrum to provide transmission links with extremely high capacities. As research progressed, many complex problems were faced in the way of achieving such a super broadband communication system. However, it also was noted that other properties of optical fibres gave them a number of inherent cost and operational advantages over copper wires and made them highly attractive for simple on/off keyed links. The various advantages of optical fibres are:

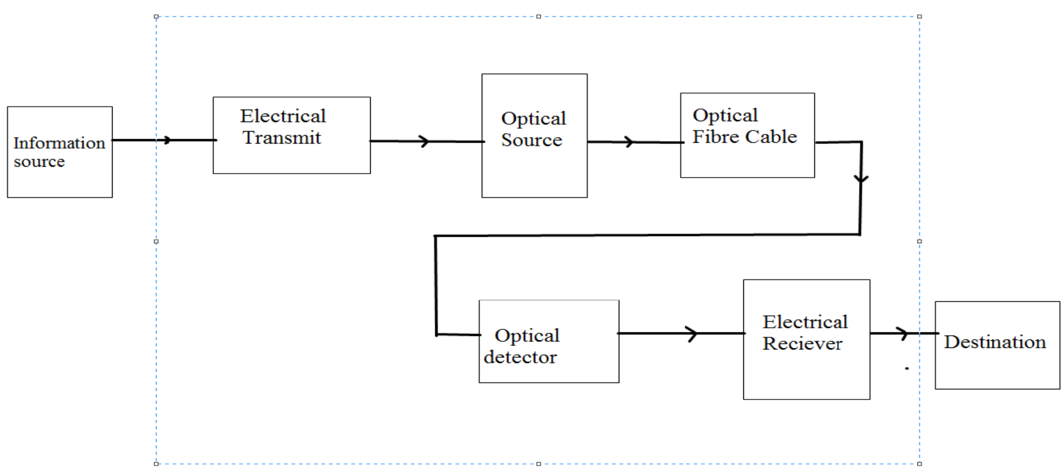


Fig 1.1 Optical fibre communication system [58]

1. *Long transmission distance*.

Optical fibres can be used to send the data over longer distances. This means that data can be sent over longer distances, they have lower transmission losses compared to copper wires thereby reducing the number of intermediate repeaters needed for these spans. This reduction in equipment and components decreases system cost and complexity.

2. *Large information capacity:*

Optical fibres can be used to send more information simultaneously over a single line, optical fibres have wider bandwidths than copper wires. This property results in a decrease in the number of physical lines needed for sending a certain amount of information.

3. *Small size and low weight*.:

The low weight and the small dimensions of fibres offer a distinct advantage over heavy, bulky wire cables in crowded underground city ducts or in ceiling-mounted cable trays. This also is of importance in aircraft, satellites, and ships where small, lightweight cables are advantageous, and in tactical military applications where large amounts of cable must be unreeled and retrieved rapidly.

4. *Immunity to electrical interference*:

An especially important feature of optical fibres[32] relates to the fact is that they do not conduct electricity. they are made up of dielectric materials, This makes optical fibres immune to the electromagnetic interference effects seen in copper wires, such as inductive pickup from other adjacent signal-carrying wires or coupling of electrical noise into the line from any type of nearby equipment.

5. *Enhanced safety:*

Optical fibres do not have the problems of ground loops, sparks, and potentially high voltages inherent in copper lines. However, precautions with respect to laser light emissions need to be observed to prevent possible eye damage.

6. *Increased signal security:*

An optical fibre has the optical signal well confined within the fibre and any signal emissions are absorbed by an opaque coating around the fibre. This offers a high degree of data security, since This is in contrast to copper wires where electric signals often can be tapped off easily.

This makes fibres attractive in applications where information security is important, such as in financial, legal, government, and military systems.

HOW DOES A FIBRE WORK

REFRACTION

Consider a flashlight. The light waves spread out along its beam. Looking down and seeing the wave crests it would appear As we move further from the light source, the wavefront gets straighter and straighter. At a long distance from the light source, the wavefront would be virtually straight. In a short interval of time each end of the wavefront would move forward a set distance. If we look at a single ray of light moving through a clear material the distance advanced by the wave front would be quite regular

There is a widely held view that light always travels at the same speed [58]. This 'fact' is simply not true. The speed of light depends upon the material through which it is moving. In free space light travels at its maximum possible speed, close to 300 million meters or nearly eight times round the world, in a second. When it passes through a clear material, it slows down by an amount dependent upon a property of the material called its *refractive index.* For most materials that we use in optic fibres, the refractive index is in the region of 1.5.

So: Speed of light in free space/speed of light in the material = refractive index

1.3 LOSSES IN OPTICAL FIBRES

Basically, there are just two ways of losing light. Either the fibre is not clear enough or the light is being diverted in the wrong direction.

ABSORPTION

Any impurities that remain in the fibre[32],[58] after manufacture will block some of the light energy. The main impurities are hydroxyl ions and traces of metals. The hydroxyl ions are actually the form of water which caused the large losses at 1380 nm. In a similar way, metallic traces can cause absorption of energy at their own particular wavelengths. These small absorption peaks are also visible. In both cases, the answer is to ensure that the glass is not contaminated at the time of manufacture and the impurities are reduced as far as possible. Now for the second reason, the diversion of the light.

RAYLEIGH SCATTERING

This is the scattering of light due to small localized changes in the refractive index of the core and the cladding material. The changes are indeed very localized. It has dimensions which are less than the wavelength of the light. There are two causes, both problems within the manufacturing processes. The first is the fluctuations in the 'mix' of the ingredients. These random changes are impossible to completely eliminate. The other cause is slight changes in the density as the silica cools and solidifies.

FRESNEL REFLECTION

When a ray of light strikes a change of refractive index and is approaching at an angle close to the normal, most of the light passes straight through. Most of the light but not all. A very small proportion is reflected back off the boundary. We have seen this effect with normal window glass. Looking at a clean window we can see two images. We can see the scene in front of us and we can also see a faint reflection of what is behind us. Light therefore is passing through the window and is also being reflected off the surface.

$$\text{Reflected power} = \frac{(n1 - n2)2}{(n1 + n2)2}$$

BENDING LOSSES

MACROBENDS

A sharp bend in a fibre can cause significant losses as well as the possibility of mechanical failure. It is easy to bend a short length of optic fibre to produce higher losses than a whole kilometer of fibre in normal use.

The normal is always at right angles to the surface of the core. Now, if the core bends, the normal will follow it and the ray will now find itself on the wrong side of the critical angle and will escape

MICROBENDS

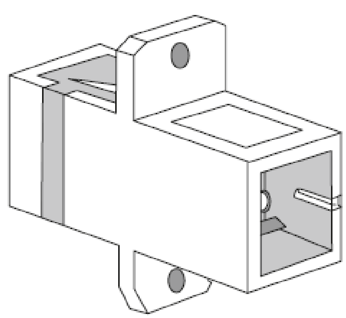
These are identical in effect to the microbend already described but differ in size and cause. Their radius is equal to, or less than, the diameter of the bare fibre – very small indeed. These are generally a manufacturing problem. A typical cause is differential expansion of the optic fibre and the outer layers. If the fibre gets too cold, the outer layers will shrink and get shorter. If the core/cladding shrinks at a slower rate, it is likely to kink and cause a microbend.

1.4 OPTICAL FIBRE CONNECTORS

Connectors and adapters are the plugs[32] and sockets of a fibre optic system. They allow the data to be re-routed and equipment to be connected to existing systems. Connectors are inherently more difficult to design than mechanical splices. This is due to the added requirement of being able to be taken apart and replaced repeatedly. It is one thing to find a way to align two fibres but it is

something altogether different if the fibres are to be disconnected and reconnected hundreds of times and still need to perform well. If two fibres are to be joined, each fibre has a connector attached and each is then plugged into an adapter. An adapter is basically a tube into which the two connectors are inserted. It holds them in alignment and the connectors are fixed onto the adapter to provide mechanical support. An adapter is shown as part of Although different makes are sold as compatible, it is good practice to use the same manufacturer for the connector and for the adapter. The design of connectors originated with the adaptation of those used for copper based coaxial cables, which were usually fitted by the manufacturers onto a few meters of fibre called a *pigtail* which was then spliced into the main system. Most connectors nowadays are fitted by the installer although pre-fitted ones are still available. The benefit of using the pre-fitted and pigtailed version is that it is much quicker and easier to fit a mechanical splice or perform a fusion splice than it is to fit a connector, so there is some merit in allowing the factory to fit the connector since this saves time.

Fig1. 2. Optical connector [58]



CONNECTOR PARAMETERS

INSERTION LOSS

This is the most important measure of the performance of a connector. Imagine we have a length of fibre which is broken and reconnected by two connectors and an in-line adapter. If the loss of the system is measured and found to have increased by 0.4 dB then this is the value of the insertion loss. It is the loss caused by inserting a mated pair of connectors in a fibre. Insertion loss for optical connectors only makes sense when considering the loss across two mated Connectors. Typical values are 0.2–0.5 dB per mated pair but the international standards recognize and allow a loss of up to 0.75 dB and this would be considered a compliant connector.

RETURN LOSS

This loss occurs when power is being reflected[4] off the connector back towards the light source.

This is a measure of the Fresnel reflection. The lasers and LEDs used for multimode working are not greatly affected by the reflected power and so the return loss is not usually quoted in this instance. In single mode systems the laser is affected and produces a noisy output. The laser suppliers will always be pleased to advise on permitted levels of return loss.

MATING DURABILITY

Also called insertion loss change. It is a measure of how much the insertion loss is likely to increase in use after it has been connected and disconnected a large number of times.

Typical value: 0.2 dB per 1000 matings.

OPERATING TEMPRATURE

These are, of course, compatible with the optic fibre cables. Typical values: 25°C to 80°C.

CABLE RETENTION

Also called tensile strength or pull-out loading. This is the loading that can be applied to the cable before the fibre is pulled out of the connector. It is similar in value to the installation tension on a lightweight cable.

Typical value: 200N.

REPEATIBILITY

This is a measure of how consistent the insertion[58] loss is when a joint is disconnected and then remade. It is not a wear-out problem like mating durability but simply a test of whether the connector and adapter are designed so that the light path is identical each time they are joined.

This is an important feature of a connector but is not always quoted in specifications owing to the difficulty in agreeing a uniform method of measuring it. Some manufacturers do give a figure for it; some just use descriptive terms like 'high' or 'very high'. The quoted insertion loss should actually be the average insertion loss over a series of matings, thus taking repeatability into account.

1.5 OPTICAL FIBRE COUPLERS

When an optic fibre carrying an input signal needs to be connected to two different destinations. The signal needs to be split into two. This is easily[4] achieved by a coupler. When used for this purpose, it is often referred to as a splitter. Couplers are bi-directional – they can carry light in either direction. Therefore the coupler described above could equally well be used to combine the signals from two transmitters onto a single optic fibre[32]. In this case, it is called a combiner.It is exactly the same device. It is just used differently .Physically, they look almost the same as a mechanical splice, If there is one fibre at each end, it is a mechanical splice; any other number and it is a coupler.

Directional couplers are passive devices used in the field of radio technology. They couple part of the transmission power in a transmission line by a known amount out through another port, often by using two transmission lines set close enough together such that energy passing through one is coupled to the other. The device has four ports: input, transmitted, coupled, and isolated.

The term "main line" refers to the section between ports 1 and 2. On some directional couplers, the main line is designed for high power operation (large connectors), while the coupled port may use a small SMA connector. Often the isolated port is terminated with an internal or external matched load (typically 50 ohms). It should be pointed out that since the directional coupler is a linear device, the notations on Figure 1.3 are arbitrary. Any port can be the input, which will result in the directly connected port being the transmitted port, the adjacent port being the coupled port, and the diagonal port being the isolated port (for stripline and microstripline couplers).

Physical considerations such as internal load on the isolated port will limit port operation. The coupled output from the directional coupler can be used to obtain the information on the signal without interrupting the main power flow in the system. When the power coupled out to port three is half the input power (i.e. 3 dB below the input power level), the power on the main transmission line is also 3 dB below the input power and equals the coupled power. Such a coupler is referred to as a 90 degree hybrid, hybrid, or 3 dB coupler. The frequency range for coaxial couplers specified by manufacturers is that of the coupling arm. The main arm response is much wider (i.e. if the spec is 2-4 GHz, the main arm could operate at 1 or 5 GHz - see Figure 3). However it should be recognized that the coupled response is periodic with frequency. For example, a $\lambda/4$ coupled line coupler will have responses at $n\lambda/4$ where n is an odd integer.

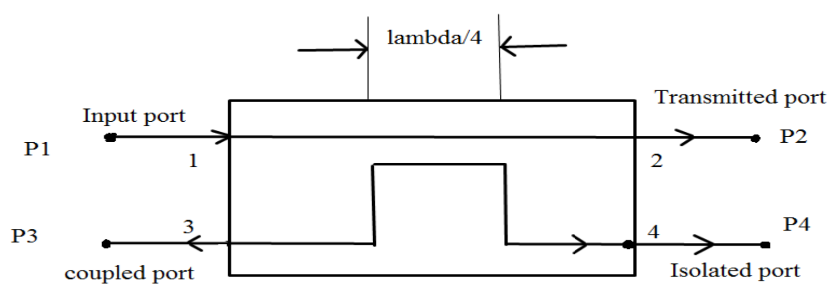


Fig 1.3. Directional coupler [32]

Common properties desired for all directional couplers are wide operational bandwidth, high directivity, and a good impedance match at all ports when the other ports are terminated in matched loads. These performance characteristics of hybrid or non-hybrid directional couplers are self-explanatory. Some other general characteristics will be discussed below.

COUPLING FACTOR

The coupling factor is defined as:

$$\text{Coupling factor(db)} = -10\log\frac{\mathrm{P3}}{P1}$$

where P_1 is the input power at port 1 and P_3 is the output power from the coupled port The coupling factor represents the primary property of a directional coupler. Coupling is not constant, but varies with frequency. While different designs may reduce the variance, a perfectly flat coupler theoretically cannot be built. Directional couplers are specified in terms of the coupling accuracy at the frequency band center. For example, a 10 dB coupling +/- 0.5 dB means that the directional coupler can have 9.5 dB to 10.5 dB coupling at the frequency band center. The accuracy is due to dimensional tolerances that can be held for the spacing of the two coupled lines. Another coupling specification is frequency sensitivity. A larger frequency sensitivity will allow a larger frequency band of operation. Multiple quarter-wavelength coupling sections are used to obtain wide frequency bandwidth directional couplers. Typically this type of directional coupler is designed to a frequency bandwidth ratio and a maximum coupling ripple within the frequency band. For example a typical 2:1 frequency bandwidth coupler design that produces a 10 dB coupling with a +/- 0.1 dB ripple would, using the previous accuracy specification, be said to have 9.6 +/- 0.1 dB to 10.4 +/- 0.1 dB of coupling across the frequency range.

LOSS

In an ideal directional coupler, the main line loss[32] from port 1 to port 2 (P_1 - P_2) due to power coupled to the coupled output port is:

$$\text{Insertion loss(db)} = 10\log\left[1 - \frac{P3}{P1}\right]$$

The actual directional coupler loss will be a combination of coupling loss, dielectric loss, conductor loss. Depending on the frequency range, coupling loss becomes less significant above 15 dB coupling where the other losses constitute the majority of the total loss.

ISOLATION

Isolation of a directional coupler can be defined as the difference in signal levels in dB between the input port and the isolated port when the two other ports are terminated by matched loads, or:

$$\text{Isolation(db)} = -10\log\left[\frac{P4}{P1}\right]$$

Isolation can also be defined between the two output ports. In this case, one of the output ports is used as the input; the other is considered the output port while the other two ports (input and isolated) are terminated by matched loads.

$$\text{Isolation(db)} = -10\log\left[\frac{P3}{P1}\right]$$

DIRECTIVITY

Directivity is directly related to isolation. It is defined as:

$$\text{Isolation(db)} = -10\log\left[\frac{P4}{P3}\right] = -10\log\left[\frac{P4}{P1}\right] + 10\log\left[\frac{P3}{P1}\right]$$

where: P_3 is the output power from the coupled port and P_4 is the power output from the isolated port. The directivity should be as high as possible. The directivity is very high at the design frequency and is a more sensitive function of frequency because it depends on the cancellation of two wave components. Waveguide directional couplers will have the best directivity. Directivity is not directly measurable, and is calculated from the isolation and coupling measurements as:

Directivity (dB) = Isolation (dB) - Coupling (dB)

1.6 FABRY PEROT FILTER

In optics, a Fabry-Pérot filter or etalon is typically made of a transparent plate with two reflecting surfaces, or two parallel highly reflecting mirrors. Its transmission spectrum as a function of wavelength exhibits peaks of large transmission corresponding to resonances of the etalon. It is named after Charles Fabry and Alfred Perot. The resonance effect of the Fabry-Pérot filter is identical to that used in a dichroic filter. That is, dichroic filters are very thin sequential arrays of Fabry-Pérot filters, and are therefore characterised and designed using the same mathematics.

Etalons are widely used in telecommunications, lasers and spectroscopy to control and measure the wavelengths of light. Recent advances in fabrication technique allow the creation of very precise tunable Fabry-Pérot filters.

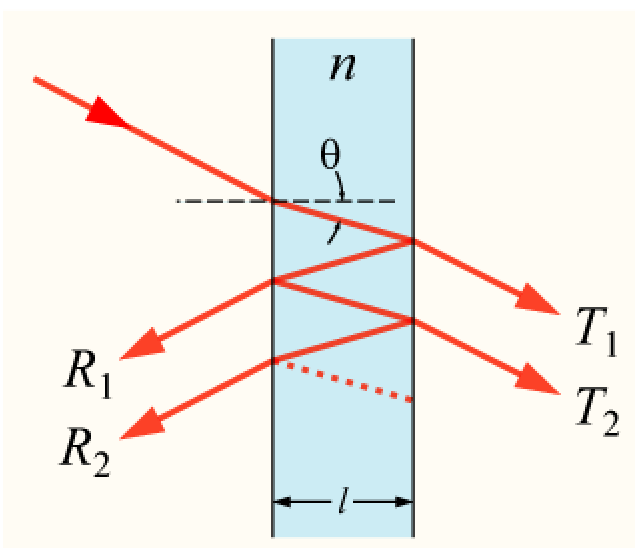


Fig 1.4 Fabry-perot filter [6]

The varying transmission function of an etalon is caused by interference between the multiple reflections of light between the two reflecting surfaces. Constructive interference occurs if the transmitted beams are in phase, and this corresponds to a high-transmission peak of the etalon. If the transmitted beams are out-of-phase, destructive interference occurs and this corresponds to a transmission minimum. Whether the multiply-reflected beams are in-phase or not depends on the wavelength (λ) of the light (in vacuum), the angle the light travels through the etalon (θ), the thickness of the etalon (*l*) and the refractive index of the material between the reflecting surfaces (*n*).The phase difference between each succeeding reflection is given by δ:

$$\delta = \left(\frac{2\pi}{\lambda}\right) 2n\mathrm{l}\cos\theta$$

A Fabry-Pérot interferometer differs from a Fabry-Pérot etalon in the fact that the distance *l* between the plates can be tuned in order to change the wavelengths at which transmission peaks occur in the interferometer. Due to the angle dependence of the transmission, the peaks can also be shifted by rotating the etalon with respect to the beam.

Fabry-Pérot interferometers or etalons are used in optical modems, spectroscopy, lasers, and astronomy.

1.7 RADIO OVER FIBRE COMMUNICATION SYSTEMS

A technology whereby light is modulated by a radio signal and transmitted over an optical fibre link to facilitate wireless access is referred to as Radio over Fibre (RoF). Although radio transmission over fibre is used for multiple purposes, such as in cable television (CATV) networks and in satellite base stations, the term RoF is usually applied when this is done for wireless access.

In RoF systems, wireless signals are transported in optical form between a central station and a set of base stations before being radiated through the air. Each base station is adapted to communicate over a radio link with at least one user's mobile station located within the radio range of said base station.

RoF transmission systems are usually classified into two main categories (RF-over-Fibre ; IF-over-Fibre) depending on the frequency range of the radio signal to be transported.

a) In RF-over-Fibre architecture, a data-carrying RF (Radio Frequency) signal with a high frequenty (usually greater than 10 GHz) is imposed on a lightwave signal before being transported over the optical link. Therefore, wireless signals are optically distributed to base stations(BS) directly at high frequencies and converted to from optical to electrical domain at the base stations before being amplified and radiated by an antenna. As a result, no frequency up/down conversion is required at the various base station, thereby resulting in simple and rather cost-effective implementation is enabled at the base stations.

b) In IF-over-Fibre architecture, an IF (Intermediate Frequency) radio signal with a lower frequency (less than 10 GHz) is used for modulating light before being transported over the optical link. Therefore, wireless signals are transported at intermediate frequency over the optical.

NEED OF RADIO OVER FIBRE SYSTEMS

For the future provision of broadband, interactive and multimedia services over wireless media, some typical characteristics are required which are-1) to reduce cell size to accommodate more users and 2) to operate in the microwave/millimeter wave (mm-wave) frequency bands to avoid spectral congestion in lower frequency bands. It demands a large number of base stations (BSs) to cover a service area, and cost-effective BS is a key to success in the market. This requirement has led to the development of system architecture where functions such as signal routing/processing, handover and frequency allocation are carried out at a central control station (CS), rather than at the BS. Furthermore, such a centralized configuration allows sensitive equipment to be located in safer environment and enables the cost of expensive components to be shared among several BSs. An attractive alternative for linking a CS with BSs in such a radio network is via an optical fibre network, since fibre has low loss, is immune to EMI and has broad bandwidth. The transmission of radio signals over fibre, with simple optical-to electrical conversion, followed by radiation at remote antennas, which are connected to a central CS, has been proposed as a method of minimizing costs. The reduction in cost can be brought about in two ways. Firstly, the remote antenna BS or radio distribution point needs to perform only simple functions, and it is small in size and low in cost. Secondly, the resources provided by the CS can be shared among many antenna BSs. This technique of modulating the radio frequency (RF) subcarrier onto an optical carrier for distribution over a fibre network is known as .radio over fibre. (RoF) technology. To be specific, the RoF network typically comprises a central CS, where all switching, routing, medium access control (MAC) and frequency management functions are performed, and an optical fibre network, which interconnects a large number of functionally simple and compact antenna BSs for wireless signal distribution. The BS has no processing function and its main function is to convert optical signal to wireless one and vice versa. Since RoF technology was first demonstrated for cordless or mobile telephone service in 1990 , a lot of research efforts have been made to investigate its limitation and develop new, high performance RoF technologies. Their target applications range from mobile cellular networks, wireless local area network (WLAN) at mm-wave bands broadband wireless access networks to road vehicle communication (RVC) networks for intelligent transportation system. Due to the simple BS structure, system cost for deploying infrastructure can be dramatically reduced compared to other wireline alternatives. In addition to the advantage of potential low cost, RoF technology has the further a benefit of transferring the RF signal to and from a CS that can allow flexible network resource management and rapid response to variations in traffic demand due to its centralized network architecture.

some of its important characteristics are described below :

1. The system control functions, such as frequency allocation, modulation and demodulation scheme, are located within the CS, simplifying the design of the BS. The primary functions of the BSs are optical/RF conversion, RF amplification, and RF/optical conversion.
2. This centralized network architecture allows a dynamic radio resource configuration and capacity allocation. Moreover, centralized upgrading is also possible.
3. Due to simple BS structure, its reliability is higher and system maintenance becomes simple.

4. In principle, optical fibre in RoF is transparent to radio interface format (modulation, radio frequency, bit rate and so on) and protocol. Thus, multiple services on a single fibre can be supported at the same time.
5. Large distances between the CS and the BS are possible.

Chapter 2

OPTICAL COMPONENT ANALYSIS

OPTICAL COMPONENET ANALYSIS

2.1 S-MATRIXREPRESENTATION OF FIBRE OPTIC COUPLERS

2.1.1 SCATTERING PARAMETERS

In a microwave circuit, when a incoming wave with amplitude[12],[13] and phase comes on a transmission line. This incoming wave is "scattered" by the circuit and its energy is partitioned between all the possible outgoing waves on all the other transmission lines connected to the circuit. The scattering parameters are fixed properties of the (linear) circuit which describe how the energy couples between each pair of ports or transmission lines connected to the circuit.

Formally, s-parameters can be defined for any collection of linear electronic components, whether or not the wave view of the power flow in the circuit is necessary. They are algebraically related to the impedance parameters (z-parameters), also to the admittance parameters (y-parameters) and to a notional characteristic impedance of the transmission lines.

An n-port microwave network has n arms into which power can be fed and from which power can be taken. In general, power can get from any arm (as input) to any other arm (as output). There are thus n incoming waves and n outgoing waves. We also observe that power can be reflected by a port, so the input power to a single port can partition between all the ports of the network to form outgoing waves.

Associated with each port is the notion of a "reference plane" at which the wave amplitude and phase is defined. Usually the reference plane associated with a certain port is at the same place with respect to incoming and outgoing waves.

In the case of a microwave network having two ports only, an input and an output, the s-matrix has four s-parameters, designated

$$\begin{pmatrix} s11 & s12 \\ s21 & s22 \end{pmatrix}$$

These four complex quantites actually contain eight separate numbers; the real and imaginary parts, or the modulus and the phase angle, of each of the four complex scattering parameters.

S- MATRIX REPRESENTATION OF POLARISATION DEPENDENT FIBRE OPTIC COUPLERS

Optical networks are in many aspects similar to microwave networks. Both consist of components like sources, couplers, modulators[12] and receivers connected by waveguides. The signals in both systems are electromagnetic waves, but optical signals have a wavelength which is five orders of magnitude smaller than microwaves, which means that the mode fields in the components are also five orders of magnitude smaller. A direct consequence is, that lengths can never be controlled in the order of magnitude of a wavelength. Furthermore in optical networks, the signals are guided by dielectric waveguides and influences of the waveguide material on the signal are not negligible. Microwave networks are most conveniently treated in terms of their S-matrices. The components are defined by their ports which are accessible to signals and their scattering parameters which define the change in phase and magnitude of the signal if it is transferred between two ports. All scattering parameters together, written in matrix form are the S-matrix of the component. It is easy to see that the S-matrix of a n-port device is a $n \times n$ matrix.

S-MATRIX FOR OPTICAL COMPONENTS

In the field of optics the S-matrix was first used to calculate the properties of fused fibre optic couplers. These devices are buildby fusing several waveguides (mostly 2 or 3) together. These optical couplers have the same number of input and output ports and show negligible reflection, which means that a signal launched at the input ports is only seen at the output ports and vice versa. They are also reciprocal e.g. the scattering parameter between two ports does not depend on the direction of signal flow. To describe optical couplers reduced S-matrices (transfer matrices) were used. A transfer matrix of a n-port device is a n/2 × n/2 matrix. For example the S-matrix of an 2 × 2 fused fibre optic coupler has the following form[13]

$$\mathbf{S}_{2\times 2} = \begin{pmatrix} 0 & 0 & ae^{j\phi_a} & be^{j\phi_b} \\ 0 & 0 & ce^{j\phi_c} & de^{j\phi_d} \\ ae^{j\phi_a} & ce^{j\phi_c} & 0 & 0 \\ be^{j\phi_b} & de^{j\phi_d} & 0 & 0 \end{pmatrix}$$

If there exists no reflection is evident from the zero submatrices. The coupler is reciprocal which causes the lower left 2 × 2 submatrix to be the Transpose of the upper right 2 × 2 submatrix. The coupler can therefore be fully described by the upper right submatrix alone which is the transfer matrix of the coupler.

$$T2 * 2 = \begin{pmatrix} ae^{j\phi a} & be^{j\phi a} \\ ce^{j\phi a} & de^{j\phi a} \end{pmatrix}$$

2.1.2 **JONES-MATRIXOF A COUPLER**

A generally polarized input field is now specified by its Jones vector The first three of the Jones matrices necessary to describe the coupler can be obtained from these expressions. Since the input field is completely arbitrary, it can be omitted and the relation with the fields after the coupler written as Jones matrices. If the light enters the coupler through fibre 2 the same modes are excited but their polarisations are rotated through 120◦, whereas if light is input through fibre 3 the modes must be rotated through 240◦.

The Jones matrices **J**21*,* **J**22*,* **J**23 are then obtained from **J**11*,* **J**12*,* **J**13[12] through rotation by 120◦.

$$J_{31} = R(\frac{4}{3}\pi)J_{12}R(\frac{4}{3}\pi)$$

$$J_{32} = R(\frac{4}{3}\pi)J_{13}R(\frac{4}{3}\pi)$$

$$J_{33} = R(\frac{4}{3}\pi)J_{11}R(\frac{4}{3}\pi)$$

CONSTRUCTION OF S-MATRIX

As pointed out before the 3 × 3 coupler can be fully described by a 6×6 S-matrix if it is reflection free and reciprocal. These properties are build into the model of propagating vector eigenmodes. The S-matrix is a 3 × 3 matrix with the Jones matrices as elements

$$S= \begin{pmatrix} j11 & j12 & j13 \\ j21 & j22 & j23 \\ j31 & j32 & j33 \end{pmatrix}$$

Most approaches use the vector modes[12] for numerical calculations to determine the free propagation constants βx

$\beta_1 x$, $\beta_2 x$ and $\beta_3 y$ not determined by symmetry considerations. However this approach requires a detailed knowledge of the transversal geometry of the coupler which is difficult to obtain if commercially available couplers are used. Calculation of the Jones matrices also requires knowledge of the coupling length *L* which is not available to the required precision

2.2 SIMULATION WORK 1

FABRY PEROT FILTER

INTRODUCTION

A Fabry-Parot Filter consist of the cavity formed by two highly reflective mirrors placed parallel to each other .The input light beam to the filter enters the first mirror at right angles to its surface. The output of the filter is the light beam leaving the second mirror. This filter is called Fabry-Parot or etalon. This is a classical device that has been used widely in interferometric applications. Fabry-Parot filters have been used for WDM in several optical network test beds. There are better filters today, such as thin film resonant multi cavity filter and they can still be viewed as Fabry-Perot filter. This type of filter transmits a narrow band of wavelengths and rejects wavelengths outside of that band. An interesting feature of this type of filter is its ability to "select" a different peak wavelength as the filter is tilted

2.2.1 THEORY

The varying transmission function of an filter is[4],[58] caused by interference between the multiple reflections of light between the two reflecting surfaces. Constructive interference occurs if the transmitted beams are in phase, and this corresponds to a high-transmission peak of the filter. If the transmitted beams are out-of-phase, destructive interference occurs and this corresponds to a transmission minimum. Whether the multiply-reflected beams are in-phase or not depends on the wavelength (λ) of the light (in vacuum), the angle the light travels through the etalon (θ), the thickness of the etalon (l) and the refractive index of the material between the reflecting surfaces (n).

The phase difference between each succeeding reflection is given by δ:

$$\delta = \left(\frac{2\pi}{\lambda}\right) 2n\mathrm{l}\cos\theta$$

If both surfaces have a reflectance R, the transmittance function of the etalon is given by:

$$Te = \frac{(1-R)2}{1+R^2-2Rcos(\delta)} = \frac{1}{(1+F\sin^2(\frac{\delta}{2})}$$

Where

$$F = \frac{4R}{(1-R)2}$$

is the *coefficient of finesse*.

Maximum transmission ($T_e = 1$) occurs when the optical path length difference ($2nl \cos \theta$) between each transmitted beam is an integer multiple of the wavelength. In the absence of absorption, the reflectance of the etalon R_e is the complement of the transmittance, such that $T_e + R_e = 1$. The maximum reflectivity is given by:

$$Rmax = 1 - \frac{1}{1+F} = \frac{4R}{(1+R)2}$$

and this occurs when the path-length difference is equal to half an odd multiple of the wavelength.

The wavelength separation between adjacent transmission peaks is called the free spectral range (FSR) of the etalon, $\Delta\lambda$, and is given by:

$$\Delta\lambda = \frac{\lambda_0^2}{2nlcos\theta + \lambda_0} = \frac{\lambda_0^2}{2nlcos\theta}$$

Where λ_0 is the central wavelength of the nearest transmission peak. The FSR is related to the full-width half-maximum, $\delta\lambda$, of any one transmission band by a quantity known as the *finesse*:

$$f = \frac{\Delta\lambda}{\delta\lambda} = \frac{\pi}{2\arcsin\left(1/\sqrt{F}\right)}$$

.This is commonly approximated (for $R > 0.5$) by

$$f = \frac{\pi\sqrt{F}}{2} = \frac{\pi\sqrt{R}}{(1-R)}$$

Etalons with high finesse show sharper transmission peaks with lower minimum transmission coefficients.

A Fabry-Pérot interferometer differs from a Fabry-Pérot etalon in the fact that the distance l between the plates can be tuned in order to change the wavelengths at which transmission peaks occur in the interferometer. Due to the angle dependence of the transmission, the peaks can also be shifted by rotating the etalon with respect to the beam.

Fabry-Pérot interferometers or etalons are used in optical modems, spectroscopy, lasers, and astronomy.

2.3 **RESULTS**

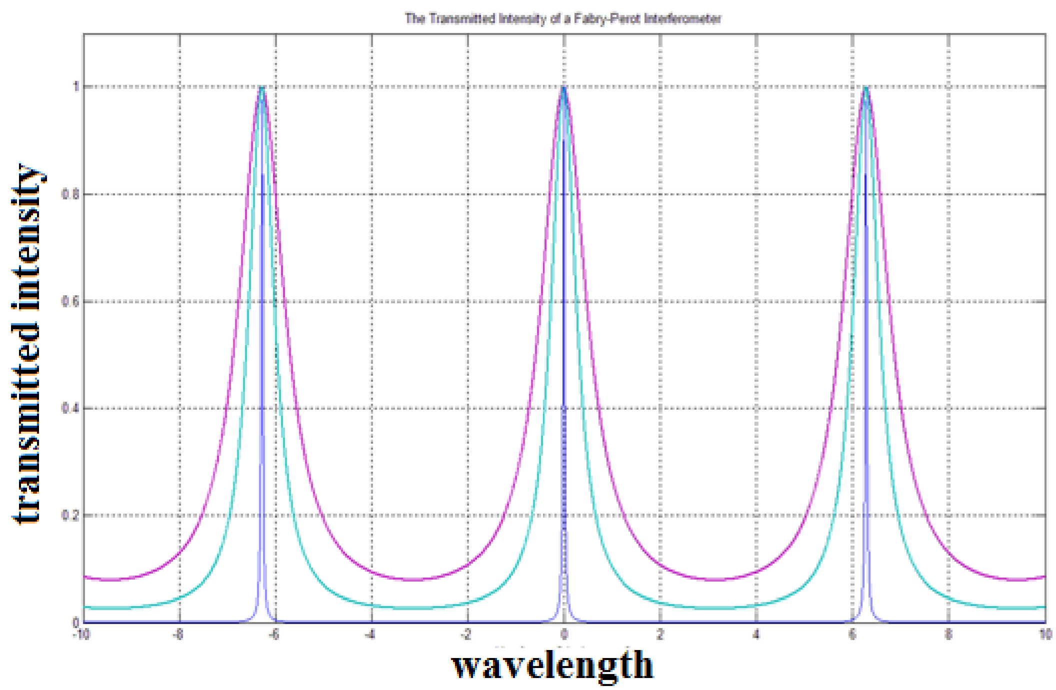


Fig 2.1 Transmitted intensity of a Fabry perot filter

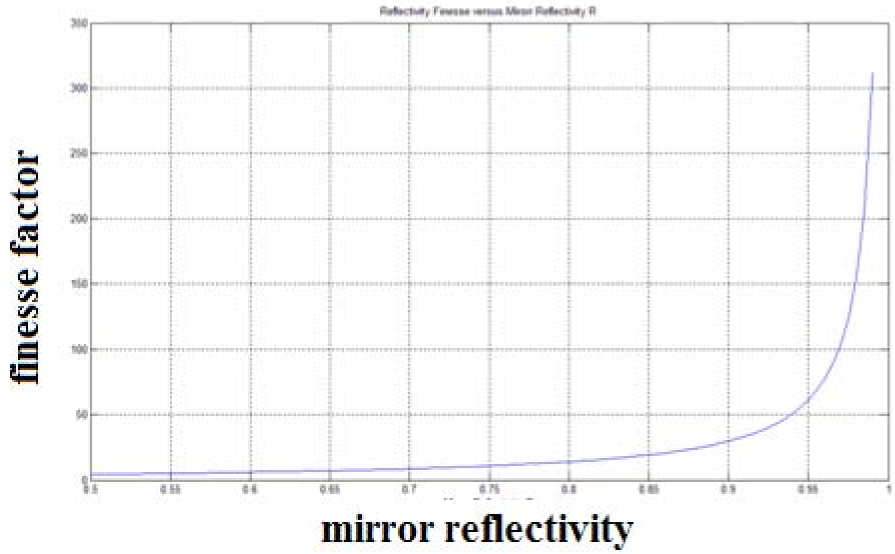


Fig 2.2 Finesse factor vs the mirror reflectivity

APPLICATIONS

- The most important common applications are as dichroic filters, in which a series of etalonic layers are deposited on an optical surface by vapor deposition. These optical filters usually have more exact reflective and pass bands than absorptive filters. When properly designed, they run cooler than absorptive filters because they can reflect unwanted wavelengths. Dichroic filters are widely used in optical equipment such as light sources, cameras and astronomical equipment.

- Telecommunications networks employing wavelength division multiplexing have add-drop multiplexers with banks of miniature tuned fused silica or diamond etalons. These are small iridescent cubes about 2 mm on a side, mounted in small high-precision racks. The materials are chosen to maintain stable mirror-to-mirror distances, and to keep stable frequencies even when the temperature varies. Diamond is preferred because it has greater heat conduction and still has a low coefficient of expansion. In 2005, some telecommunications equipment companies began using solid etalons that are themselves optical fibres. This eliminates most mounting, alignment and cooling difficulties.

- Laser resonators are often described as Fabry-Pérot resonators, although for many types of laser the reflectivity of one mirror is close to 100%, making it more similar to a Gires-Tournois interferometer. Semiconductor diode lasers sometimes use a true Fabry-Pérot geometry, due to the difficulty of coating the end facets of the chip.

- Fabry-Pérot etalons can be used to prolong the interaction length in laser absorption spectrometry techniques.

- A Fabry-Pérot etalon can be used to make a spectrometer capable of observing the Zeeman effect, where the spectral lines are far too close together to distinguish with a normal spectrometer.

- In astronomy an etalon is used to select a single atomic transition for imaging. The most common is the H-alpha line of the sun. The Ca-K line from the sun is also commonly imaged using etalons

Chapter 3

RADIO OVER FIBRE SYSTEMS

3.1 RADIO **OVER FIBRE SYSTEMS**

Wireless networks based on RoF technologies have been proposed as a promising cost-effective solution to meet ever increasing user 0bandwidth and wireless demands. Since it was first demonstrated for cordless or mobile telephone service in 1990 [5],[6],[8] a lot of research has been carried out to investigate its limitation and develop new and high performance RoF technologies. In this network a CS is connected to numerous functionally simple BSs via an optic fibre. The main function of BS is to convert optical signal to wireless one and vice versa. Almost all processing including modulation, demodulation, coding, routing is performed at the CS. That means, RoF networks use highly linear optic fibre links to distribute RF signals between the CS and BSs. Fig shows a general RoF architecture. At a minimum, an RoF link consists of all the hardware required to impose an RF signal on an optical carrier, the fibre-optic link, and the hardware required to recover the RF signal from the carrier. The optical carrier's wavelength is usually selected to coincide with either the 1.3 um window, at which standard single-mode fibre has minimum dispersion, or the 1.55 um window, at which its attenuation is minimum.

This topic has two parts.

first part is dedicated to a description of general optical transmission link, where digital

signal transmission is assumed as current optical networks. The second part mainly deals with RoF technologies and is subdivided as follows: (1) RoF link characteristics, requirements, (2) RF signal generation and transportation techniques, and link configurations (3) the state of the art on mm-wave generation and transport technologies.

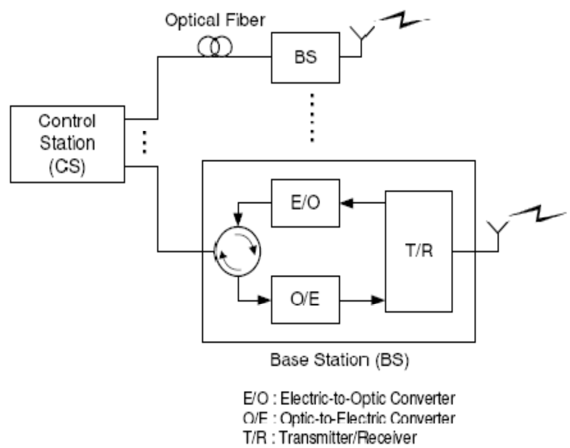


Fig 3.1 General Radio over Fibre system [6]

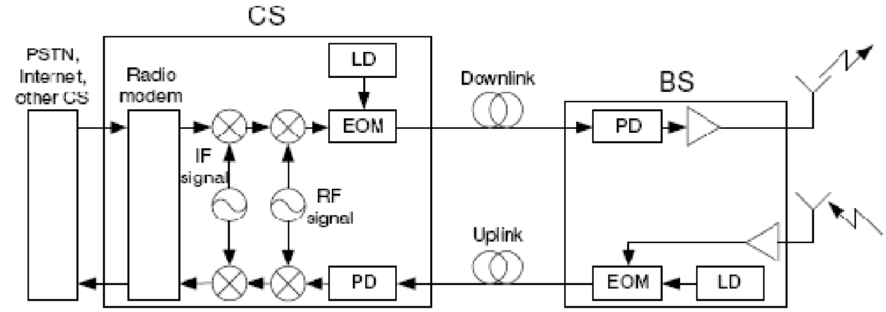
RADIO OVER FIBRE OPTICAL LINKS

INTRODUCTION

Unlike conventional optical networks where digital signal is mainly transmitted, RoF is fundamentally an analog transmission system because it distributes the radio waveform, directly at the radio carrier frequency, from a CS to a BS. Actually, the analog signal that is transmitted over the optical fibre can either be RF signal, IF signal or baseband (BB) signal. For IF and BB transmission case, additional hardware for up-converting it to RF band is required at the BS. At the optical transmitter, the RF/IF/BB signal can be imposed on the [7] optical carrier by using direct or external modulation of the laser light. In an ideal case, the output signal from the optical link will be a copy of the input signal. However, there are some limitations because of non-linearity and frequency response limits in the laser and modulation device as well as dispersion in the fibre. The transmission of analog signals puts certain requirements on the linearity and dynamic range of the optical link. These demands are different and more exact than requirements on digital transmission systems

3.1.1 **ROF LINK CONFIGURATIONS**

A typical RoF link configuration is classified based on the kinds of frequency bands (baseband (BB), IF, RF bands) transmitted over an optical fibre link. Here, we assume that a BS has its own light source for explanation purpose, however, BS can be configured without light source for uplink transmission. In each configuration, BSs do not have any equipment for modulation and demodulation, only the CS has such equipment. In the downlink from the CS to the BSs, the information signal from a public switched telephone network (PSTN), the Internet, or other CS is fed into the modem in the CS. The signal that is either RF, IF or BB bands modulates optical signal from LD. if the RF band is low, we can modulate the LD signal by the signal of the RF band directly. If the RF band is high, such as the mm-wave band, we sometimes need to use external optical modulators (EOMs), like electroabsorption ones. The modulated optical signal is transmitted to the BSs via optical fibre. At the BSs, the RF/IF/BB band signal is recovered to detect the modulated optical signal by using a PD. The recovered signal, which needs to be upconverted to RF band if IF or BB signal is transmitted, is transmitted to the MHs via the antennas of the BSs. In the configuration, the modulated signal is generated at the CS in an RF band and directly transmitted to the BSs by an EOM, which is called .RF-over-Fibre.. At each BS, the modulated signal is recovered by detecting the modulated optical signal with a PD and directly transmitted to the MHs. Signal distribution as RF-over-Fibre has the advantage of a simplified BS design but is susceptible to fibre chromatic dispersion that severely limits the transmission distance. In the configuration, the modulated signal is generated at the CS in an IF band and transmitted to the BSs by an EOM, which is called .IF-over-Fibre. At each BS, the modulated signal is recovered by detecting the modulated optical signal with a PD, upconverted to an RF band, and transmitted to the MHs. In this scheme, the effect of fibre chromatic dispersion on the distribution of IF signals is much reduced, although antenna BSs implemented for RoF system incorporating IF-over- Fibre transport require additional electronic hardware such as a mm-wave frequency LO for frequency up- and downconversion. In the configuration (c) of the figure, the modulated signal is generated at the CS in baseband and transmitted to the BSs by an EOM, which is referred to as .`BB-over-Fibre.. At each BS, the modulated signal is recovered by detecting the modulated optical signal with a PD, upconverted to an RF band through an IF band or directly, and transmitted to the MHs. In the baseband transmission, influence of the fibre dispersion effect is negligible, but the BS configuration is the most complex. Since, without a subcarrier frequency, it has no choice but to adopt time-division or code division multiplexing. In the configuration (d), the modulated signal is generated at the CS in a baseband or an IF band and transmitted to the BSs by modulating a LD directly. At each BS, the modulated signal is recovered by detecting the modulated optical signal with a PD, unconverted to an RF band, and transmitted to the MHs. This is feasible for relatively low frequencies, say, less than 10 GHz. By reducing the frequency band used to generate the modulated signal at the CS such as IF over- Fibre or BB-over-Fibre, the bandwidth required for optical modulation can greatly be reduced. This is especially important when RoF at mm-wave bands is combined with dense wavelength division multiplexing (DWDM). However, this increases the amount of equipment at the BSs because an up converter for the downlink and a down converter for the uplink are required. In the RF subcarrier transmission, the BS configuration can be simplified only if a mm-wave optical[6],[8] external modulator and a high-frequency PD are respectively applied to the electric-to-optic (E/O) and the optic-to-electric (O/E) converters. For the uplink from an MH to the CS, the reverse process is performed. In the configuration shown in (a), the signals received at a BS are amplified and directly transmitted to the CS by modulating an optical signal from a LD by using an EOM. In the configuration (b) and (c), the signals received at a BS are amplified and downconverted to an IF or a baseband frequency and transmitted to the CS by modulating an optical signal from a LD by using an EOM. In the configuration (d), the signals received at a BS are amplified and downconverted to an IF or a baseband frequency and transmitted to the CS by directly modulating an optical signal from a LD.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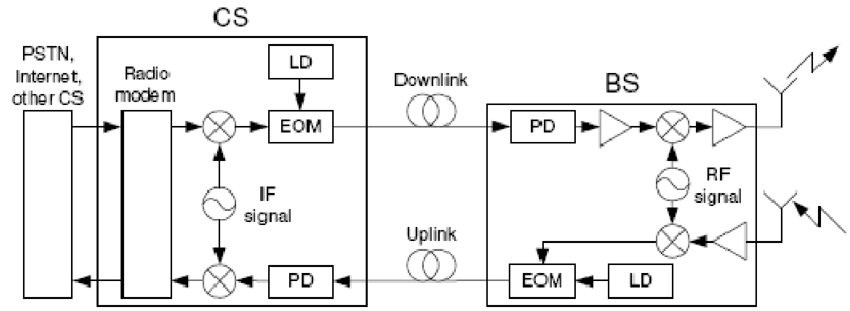
(a)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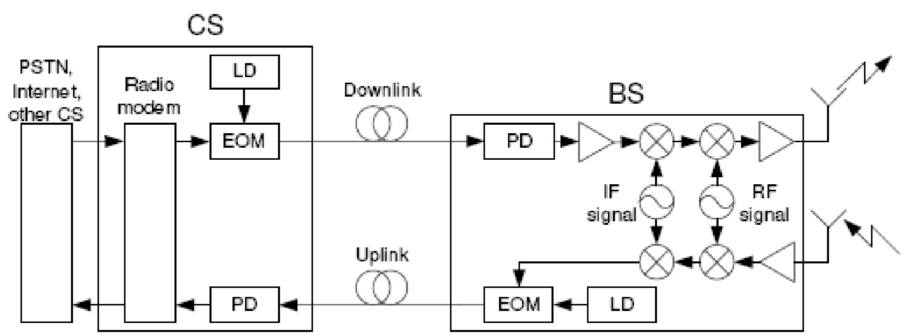
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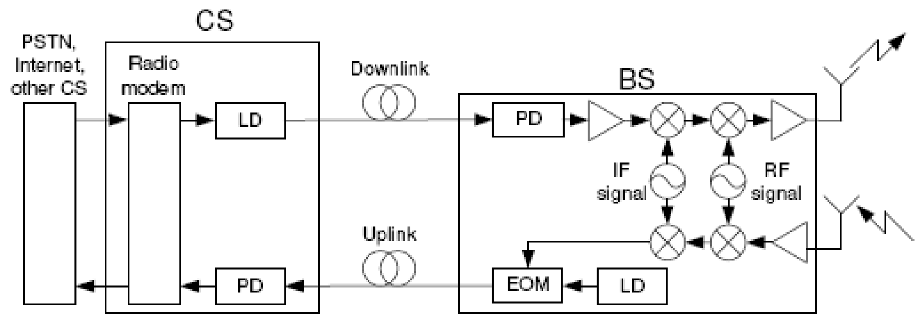

(d)

Fig 3.2

a. RF modulated signal
b. IF modulated signal
c. BB modulated signal
d. Direct modulation[6]

3.2 MILLIMETER WAVE BAND CHARACTERISTICS

Due to spectrum congestion in microwave bands and, the interest of researchers and standardization bodies has indicated the mm-wave band[4] as a candidate for some of
the most challenging services to be provided in the future . However, the use of the mm-wave band introduces some features that have to be taken into account in system design; these features are mainly related to the short wavelength and to the additional attenuation due to rain and oxygen absorption, when present.

WHY MILLIMETER WAVES?

The main advantages on the usage of mm-waves can be summarized as follows:
1. The high power level attenuation, due to the large value of frequency, in conjunction with oxygen and rain absorption, which leads to a high spatial filtering effect with the consequent frequent channel reuse;
2. The small size of antennas and RF circuits;

3. The large spectrum availability.

On the other hand, large values of signal attenuation become a fundamental drawback when long-distance communication links are to be managed. Hence, significant applications of the mm-wave can be found in the field of short-range communication systems, i.e., when link distances range from a few meters up to one kilometer Another useful consequence of the mm-wave band utilization, related to the large values of attenuation, is the low number of interfering signal sources that are usually present in the system. Both in indoor environments, due to walls, and in outdoor scenarios, due to high frequency, a number of interferers ranging from zero to two or three may be present. This represents a signi_cant advantage in terms of capture probability when packet communications and narrow-band signaling are considered.

MILLIMETER WAVE GENERATION TECHNIQUES

Recently, a lot of research has been carried out to develop mm-wave[4] generation and transport techniques, which include the optical generation of low phase noise wireless signals and their transport overcoming the chromatic dispersion in fiber. Several state-of-the-art techniques that have been investigated so far are described in this section, which are classified into the following four categories :

1. optical heterodyning
2. external modulation
3. up- and down-conversion
4. optical transceiver

ROF AND WAVELENGTH DIVISION MULTIPLEXING

The application of WDM in RoF networks has many advantages including simpli_cation of the network topology by allocating different wavelengths to individual BSs, enabling easier network and service upgrades and providing simpler network management. Thus, WDM in combination with optical mm wave transport has been widely studied. A schematic arrangement is illustrated in Fig, where for simplicity, only downlink transmission is depicted. Optical mm-wave signals from multiple sources are multiplexed and the composite signal is optically amplified, transported over a single fibre, and demultiplexed to address each BS. Furthermore, there have been several reports on dense WDM (DWDM) applied to RoF networks. Though a large number of wavelengths is available in the modern DWDM technologies, since mm-wave bands RoF networks may require even more BSs wavelength resources should be efficiently utilized. A challenging issue is that the optical spectral width of a single optical mm-wave source may approach or exceed WDM channel spacing

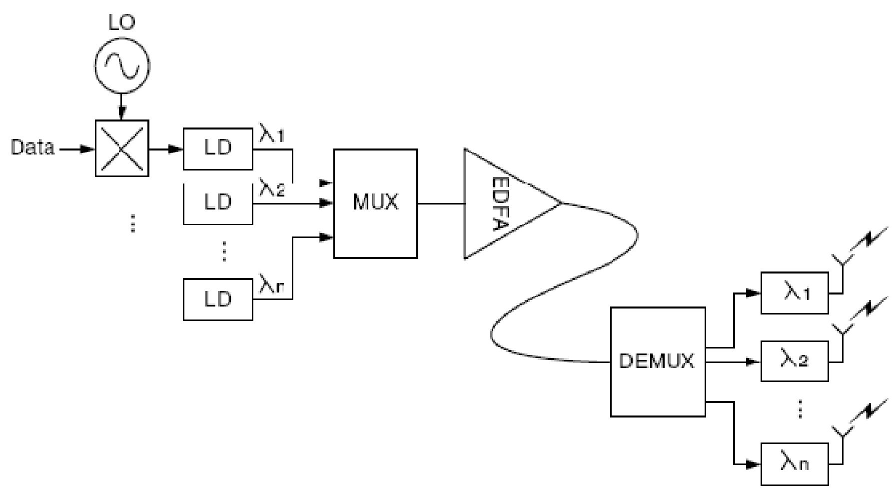

Fig 3.3 Combination of DWDM and ROF configuration[6]

3.3 SIMULATION WORK 2

POWER SPECTRUM MEASUREMENTS OF A MILLIMETER WAVE RADIO OVER FIBRE SYSTEM

INTRODUCTION

For a high speed wireless local or personal area network millimeter[37][39] wave communication systems can be used. In this simulation work the power spectrum measurements of a 1.25 gbps radio overfibre system at 60ghz. Millimeter wave at 58.1 ghz is modulated using binary phase shift keying(BPSK) The power spectrum of ROF link output is examined as a function of fibre length. Again, the use of optical filter to remove fading effect in the power spectrum is conducted and the effect of modulating frequency on power spectrum is discussed.

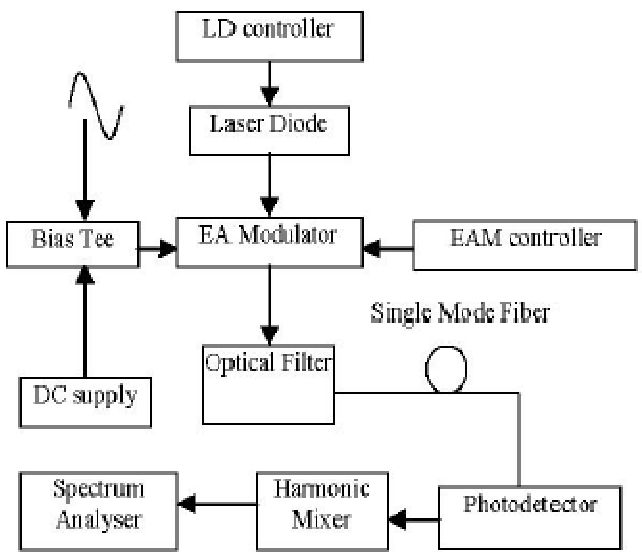

Fig 3.4 Setup for power spectrum measurements[37]

3.3.1 THEORY

When we use an optical filter at 58.1GHz. The power level experiences a dip in some regions of length that display bit errors in the BER measurements. The introduction of the optical filter improves the SNR in the regions of fibre lengths with bit error problems. However, the loss introduced by the optical filter is around 12dB. if transmission is done at two millimeter wave frequencies without filter inserted. When the transmitted frequency is higher, the power is smaller for the same fibre length. Low power level leads to high bit error rate. By comparing BER with results here, the minimum power level before error occurs is -75.6dBm without any adjustment for gain provided by amplifiers. Different frequency components in light spectra travel with different speed in optical fibre. The photodetector[37] carries out direct demodulation of optical signals. Destructive interference results when the upper sideband and lower sideband is π radians out of phase. The normalized power after transmission in the dispersive fibre is given by

$$P(f,L)=\left[e^{-\alpha_L L}\sqrt{1+\alpha_H^2}\cos\left(\frac{\pi\lambda^2 DLf^2}{c}+\tan^{-1}\alpha_H\right)\right]^2$$

where a_L, a_H, i, c, L, and f are the fibre propagation loss, chirp parameter of EA modulator, wavelength of the optical carrier, speed of light in vacuum, fibre length and frequency of modulating signal respectively. Fading occurs when the argument of cosine in Equation is odd multiples of π^2. The lengths of fibre where fading will occur are given by

$$L=\frac{c}{\pi\lambda^2 Df^2}\left[(2k-1)\frac{\pi}{2}-\tan^{-1}\alpha_H\right]$$

where k= 1, 2, 3, ... For a 60GHz modulating frequency, the length at which fading occurs are 612m, 2.758km and 4.903km for k = 1, 2 and 3 respectively. The regions around these lengths coincide with the regions with the BER measurements.

3.3.2 RESULTS AND DISCUSSION

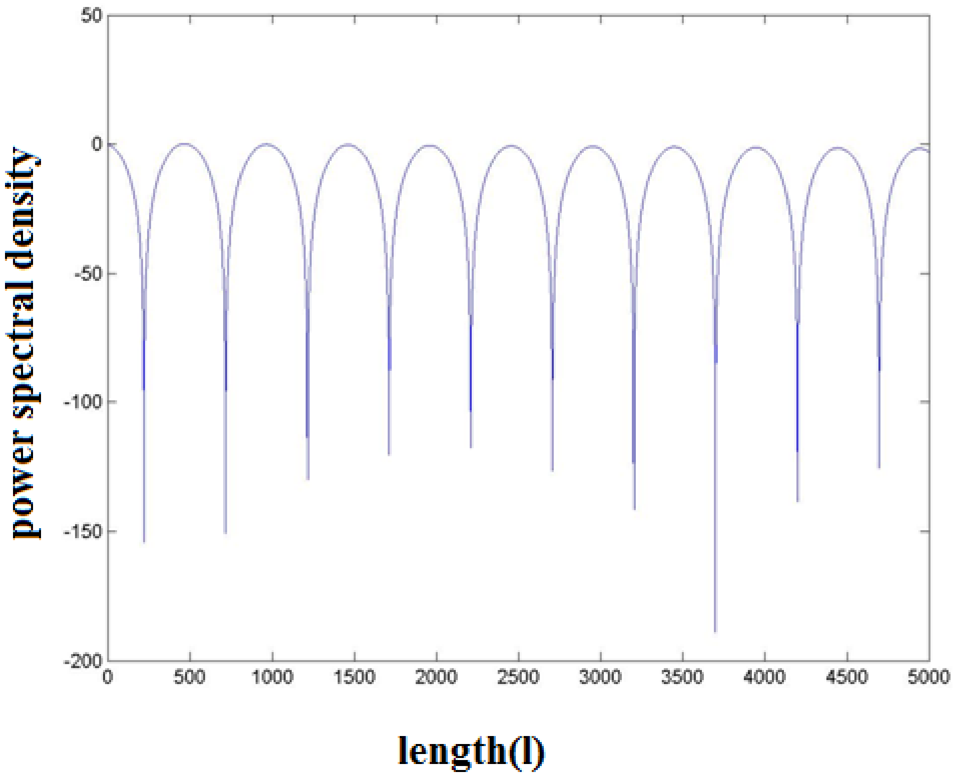

Fig 3.5 Power spectrum from photo detector at 58.1 ghz

Figure 3.5 compares the effect of the use of an optical filter at 58.1GHz. The power level experiences a dip in the same regions of length that display bit errors in the previous section for the BER measurements. The introduction of the optical filter improves the SNR in the regions of fibre lengths with bit error problems. However, the loss introduced by the optical filter is around 12dB.

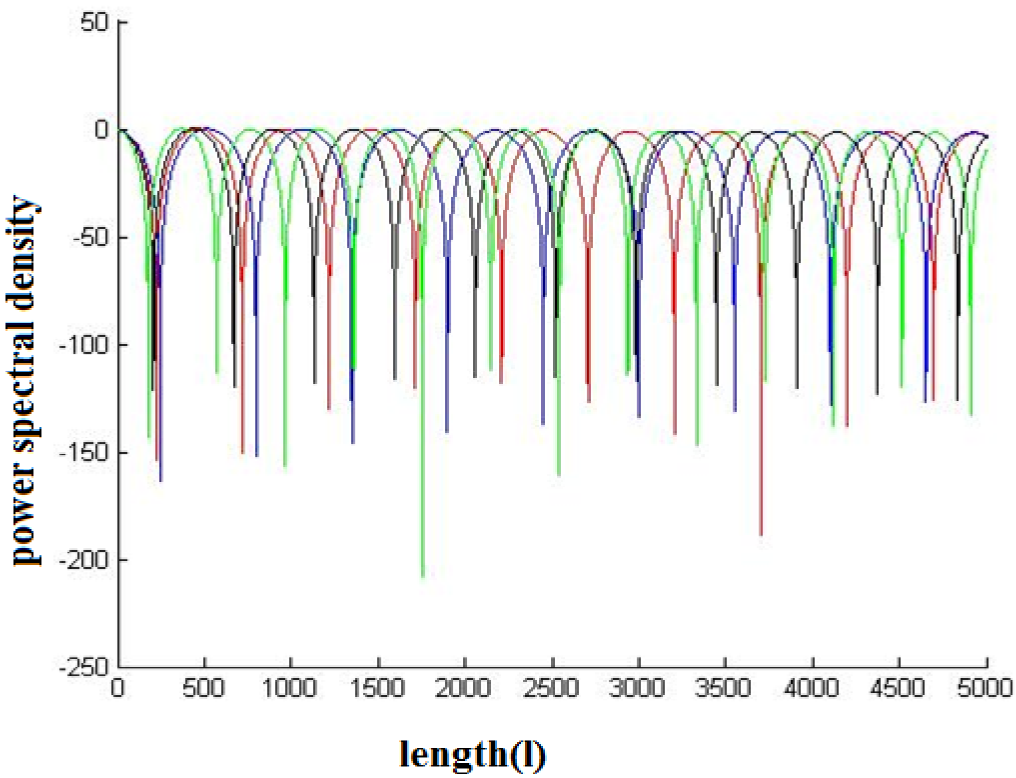

Fig 3.6 Power spectrum from photo detector at various frequencies

Fig 3.6 shows the Power spectrum of the Photodetector at various frequencies the Frequencies used here are 55 Ghz, 58.1GHz and 60Ghz we observe that The power level experiences a dip in the same regions of length that display bit errors for the BER measurements. The introduction of the optical filter improves the SNR in the regions of fibre lengths

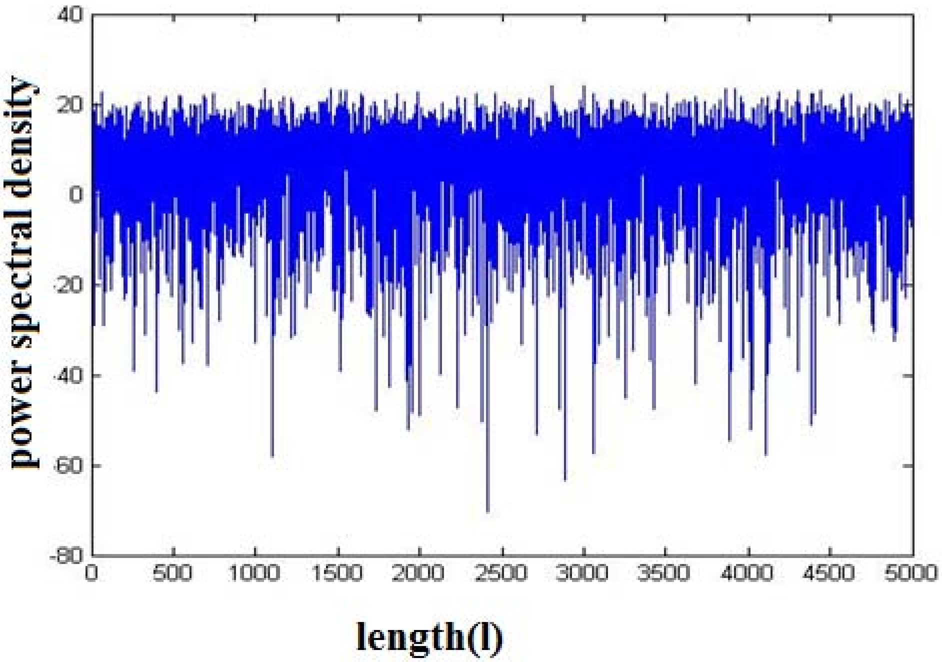

Fig 3.7 Power spectrum with noise in the channel

Fig 3.7 shows the Power spectrum of the Photodetctor when the channel noise(Guassian) is there in the channel It distorts the power Spectrum and a filter has to be used to remove the noise the filter used is DIcone tunable band pass filter.

3.4 SIMULATION WORK 3

IMPACT OF NON LINEAR DISTORTION IN RADIO OVER FIBRE SYSTEMS WITH SINGLE SIDE BAND AND TANDEM SINGLE SIDE BAND SUBCARRIER MODULATIONS

INTRODUCTION

Microwave and millimeter-wave band radio over fibre (RoF) system scan[43],[47] be applied combined with dense wavelength-division multiplexing (DWDM) for the future wireless acess networks. To improve optical spectral efficiency in transmission and reduce chromatic dispersion impact on transmission, two subcarrier modulations (SCMs), i.e., single-sideband modulation (SSB) and tandem single-sideband (TSSB) modulations, were proposed and demonstrated. The two SCMs both can be realized by using optical Mach–Zehnder modulators (MZMs), which have a cosine transfer function theoretically in the electric field domain. In other words, MZMs have the nonlinear transfer function, leading to nonlinear distortion consisting of harmonic distortion (HD) and intermodulation distortion (IMD) when radio frequency (RF) signals electrically drive an MZM. The IMDs can be further increased when multiple RF signals or frequencydivision-Multiplexed (FDM) signals drive an MZM simultaneously (i.e., one wavelength carries multiple RF signals). Such nonlinear distortions will considerably reduce receiver sensitivity and dynamic range, and thus, RoF system performance. For the SSB SCM, multiple RF or FDM signal tones carried by one wavelength or optical carrier are located in either lower sideband (LSB) or upper sideband (USB) of the optical carrier, whereas for the TSSB SCM, one half of multiple RF signals or FDM signal tones are located in LSB and the others in USB of the optical carrier. Therefore, the optical spectral efficiency with both SCMs can be the same in DWDM RoF systems. Intuitively, it should be expected that the two SCMs should result in similar nonlinear distortion for a similar RoF system setup. However, we will see that nonlinear distortions in RoF systems using the SSB and TSSB SCMs may be different, strongly depending on optical modulation index and frequency difference of two RF signals as well as transmission fibre. To achieve high-capacity wireless access networks, very dense WDM systems have to be used, which can be combined with microcell and picocell wireless networks. In addition, the impact of nonlinear distortion was investigated only for DWDM RoF systems using SSB SCM with a small modulation index. However, a large modulation index is usually preferred in RoF systems, but serious nonlinear distortion may be induced. Here we theoretically investigate nonlinear distortion impact in RoF systems using both SSB and TSSB SCMs combined with simulation.

3.4.1 ROF SYSTEMS USING TSSB SCM

THEORY

The first case is of nonlinear distortion in an RoF system usingTSSB SCM. Fig. shows the schematic of such a system. Two RF signals drive an MZM, and after fibre transmission, an optical filter with bandwidth of 12 GHz is used to model DWDM multiplexer/demultiplexer with channel spacing of 12.5 GHz. After photodetection, two bandpass electrical filters are used
to extract the RF signals. Finally, to evaluate the impact of nonlinear distortion, noise-to-signal ratio (NSR) is calculated considering all possible nonlinear distortions. The nonlinear distortion is comprised of HDs and IMDs, the magnitudes of which are at least dependent on optical modulation index of $\xi\pi = \pi Vm/V\pi$, where Vm[43] is RF modulation voltage at two arms of an MZM, and $V\pi$ is the voltage of inducing a π phase shift in each arm of the MZM. The frequency locations of the HDs and IMDs are dependent on two subcarrier frequencies Ω1 and Ω2 in the optical domain or RF carrier frequencies Ω1 and Ω2 in the electrical domain. We consider three cases, i.e., 1) Ω2 − Ω1 = 3 GHz, 2) Ω2 − Ω1 =2 GHz, and 3) Ω2 − Ω1 = 1 GHz. If beyond 3 GHz, the optical spectral efficiency is reduced, and if below 1 GHz, interference between two RF signals may be introduced.

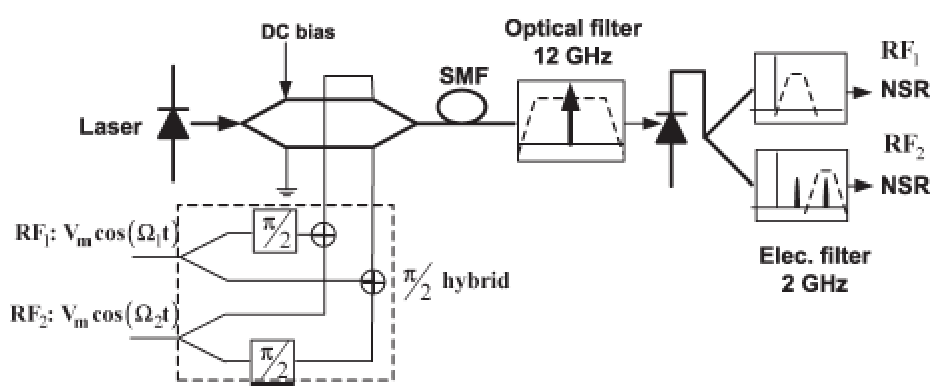

Fig 3.8 Schematic of ROF system using TSSB SCM [43]

We derive nonlinear distortion in an RoF system with TSSB SCM by using an MZM. As shown in Fig. 1, two sets of RF signals, with RFs of Ω1 and Ω2, drive a four-port 90◦ hybrid. The two hybrid outputs drive a dual-arm MZM [10], biased at quadrature. When a continuous-wave (CW) electric field of $E_0e^{j\omega t}$, ω-optical carrier frequency is injected into the MZM, the output electric field after transmission over fibre with a length of L is given by

$$E_{out} = \frac{E0}{\sqrt{2}}\{\sqrt{2} * j0 * j0 * (f) cos(w * t + (.25 * \pi)$$

$$-2(j0)(j1)\cos(wt+\Omega 1(t)-(b1(\Omega 1)l)-(.5b2(\Omega 1)(\Omega 1)l))$$

$$-2(j0)(j1)^2\sin(wt-(\Omega 2)t+(b1(\Omega 2)l)-(.5b2(\Omega 2)^2 l))$$

$$+\sqrt{2}(j1)^3\sin(wt+(\Omega 2-\Omega 1)t-(.25\pi)-(b1(\Omega 2-\Omega 1)l)-(.5b2(\Omega 2-\Omega 1)(\Omega 2-\Omega 1)l))$$

$$-\sqrt{2}(j1)^2\sin(wt-(\Omega 2-\Omega 1)t-(.25\pi)+(b1(\Omega 2-\Omega 1)l)-(.5b2(\Omega 2-\Omega 1)(\Omega 2-\Omega 1)l))$$

$$+\sqrt{2}(j1)^2\sin(wt+(\Omega 2+\Omega 1)t+(.25\pi)-(b1(\Omega 2+\Omega 1)l)-(.5b2(\Omega 2-\Omega 1)(\Omega 2-\Omega 1)l))$$

$$+2(j1)(j2)\cos(wt-(2\Omega 2-\Omega 1)t+(b1(2\Omega 2-\Omega 1)l)-(.5b2(2\Omega 2-\Omega 1)(2\Omega 2-\Omega 1)l))$$

$$-2(j1)(j2)\sin(wt-(2\Omega 1-\Omega 2)t+(b1(2\Omega 1-\Omega 2)l)-(.5b2(2\Omega 1-\Omega 2)(2\Omega 1-\Omega 2)l))$$

$$+\sqrt{2}(j0)(f)(j2)(f)\cos(wt+(2\Omega 1t)-(.25\pi)-(2b1(\Omega 1)l)-(2b2(\Omega 1)^2 l))$$

$$+\sqrt{2}(j0)(j2)\cos(wt-(2\Omega 1t)-(.25\pi)+(2b1(\Omega 1)l)-(2b2(\Omega 1)^2 l))$$

$$-(2(j2)^4\cos(wt+(2\Omega 2-\Omega 1)t+(.25\pi)-2b1(\Omega 2-\Omega 1)l-(2b2(\Omega 2-\Omega 1)(\Omega 2-\Omega 1)l))$$

$$-2(j2)^2\cos(wt-(2\Omega 2-\Omega 1)t+(.25\pi)+2b1(\Omega 2-\Omega 1)l-(2b2(\Omega 2-\Omega 1)(\Omega 2-\Omega 1)l))$$

$$+2(j1)(j3)\sin(wt-(3\Omega 1-\Omega 2)t-(.25\pi)-(2b1(3\Omega 1-\Omega 2)l)-(.5(b2(3\Omega 1-\Omega 2)(3\Omega 1-\Omega 2)l)))\Big)\Big\} \quad \ldots\ldots (1)$$

where $Jk()$ is the Bessel function of first kind, $k = 0, 1, 2, 3, \ldots, \xi\pi = \pi Vm/V\pi$ is the optical modulation index or depth, Vm is the RF modulation voltage at two arms, and $V\pi$ is the voltage of inducing a π phase shift in each arm of the MZM.

Where b1 and *b*2 denote the first and second derivatives of the propagation constant with respect to the optical carrier frequency.

There are a number of HDs and IMDs in the electrical domain, which may interfere with the two RF signals. One method for estimating nonlinear distortion impact is to use the ratio of each HD or each IMD to RF signal in power . Thus, there are several ratios for different HDs and IMDs, and it is impossible to have an entire picture of nonlinear distortion impact on RoF systems. Here, we use NSR, considering all possible HDs and IMDs to estimate the impact of nonlinear distortion. NSR is given in Table I for different RF frequencies of Ω1 and Ω2.

Ω1 Ghz	Ω2 Ghz	Non linear distortion frequencies for Ω1	Non linear distortion frequencies for Ω2	RF Ω1 NSR	RF Ω2 NSR
1	4	2 Ω1,(Ω2-2 Ω1)	3 Ω1,(Ω2- Ω1),(Ω2-Ω1)	NSR(1a)	NSR(2a)
2	5	(Ω2- Ω1), (Ω2-2Ω1)	3 Ω1, 2 Ω1, 2(Ω2- Ω1)	NSR(1b)	NSR(2b)
3-5	6-8	(Ω2- Ω1)	3 Ω1, 2(Ω2- Ω1)	NSR(1c)	NSR(2c)
6-7	9-10	2 (Ω2- Ω1)	(3Ω1- Ω2)	NSR(1d)	NSR(2d)

Table 1 NSR for optical carrier having TSSB SCM with (Ω2 − Ω1) = 3[43]

Where

NSR(1a)=

$$10\log[(2(j0)^2(j2)^2\sin^2(2b2(\Omega1)(\Omega1)l)+((j1)(j1)(j2)(j2))/((j0)^2((j1)^2))]$$

$$NSR(2a)=10\log[(2(j1)^2\sin^2(.5b2(\Omega2)(\Omega1)(\Omega2)(\Omega1)l+(2((j1)^4)\sin^2(.5b2(\Omega2+\Omega1)(\Omega2+\Omega1)l)+((j0)^2((j3)^2/((j0)^2(j1)^2)]$$

$$NSR(1b)= 10\log[(2(j1)^2\sin^2(.5(b2)(\Omega2-\Omega1)(\Omega2-\Omega1)l)+(j2)^2/((j0)^2)]$$

$$NSR(2b)=10\log[((j0)^2(j2)^2\sin^2(2(\Omega1)^2l)+2(j2)^4 +(j0)^2(j3)^2)/((j0)^2((j1)^2))]$$

NSR(1c)=

$$10\log[(2(j0)^4(j1)^2\sin^2(.5(b2)(\Omega2-\Omega1)(\Omega2- \Omega1)l)+4(j1)^2(j2)^4)/((j0)^6]$$

$$NSR(2c)= 10\log[((j0)^2(j2)^2\sin^2(2(\Omega1)^2l)+2(j2)^4)/((j0)^2(j1)^2)]$$

$$NSR(1d)=10\log[((j2)^4(j0)^2\sin^2(2b2(\Omega2-\Omega1)(\Omega2-\Omega1)l) +2(j1)^2(j2)^2(j3)^2)/((j0)^4(j1)^2)]$$

$NSR(2d)= \quad 10log[(2(j3)^2 sin^2(.5b2(3\Omega1-\Omega2)(3\Omega1-\Omega2)l))/((j0)^2(j0))]$

For the case of Ω2 − Ω1 = 1 GHz, the two RF signals may interfere with each other, but these were not considered. Suppose that any HDs and IMDs that are located in between the two RF signals in frequency are considered to be nonlinear distortion for both RF signals. Practically, electrical bandpass filters with a bandwidth of less than 2 GHz to extract the two RF signals should be used to reduce two RF signal mutual interference. This implies that our NSR may overestimate nonlinear distortion-induced interference. The frequency locations of some HDs and IMDs for the different combinations of Ω1 and Ω2 ., it is obviously seen that some nonlinear distortions in frequency are shifted closer to or farther than the RF signals at Ω1 and Ω2. These frequency shifts will alter NSR. Correspondingly, NSRs of RF signals at Ω1 and Ω2 are given in Table 2

Ω1 Ghz	Ω2 Ghz	Non linear distortion frequencies for Ω1	Non linear distortion frequencies for Ω2	RF Ω1 NSR	RF Ω2 NSR
1	2	2 Ω1,(Ω2- Ω1)	2 Ω1,3 Ω1,(Ω2+Ω1), (2Ω2-Ω1)	NSR(3a)	NSR(4a)
2	3	(Ω2- Ω1), (Ω2-2Ω1)	2 Ω1, (2 Ω2- Ω1)	NSR(3b)	NSR(4b)
3-9	4-10	(Ω2- 2Ω1)	(2Ω2- Ω1)	NSR(3c)	NSR(4c)

Table 2 NSR for one optical carrier having TSSB SCM with (Ω2 − Ω1) = 1[43]

Where

$NSR(3a)=10log[(2(j1)^4 sin^2(.5(b2)(\Omega2-\Omega1)^2 l)+ (j0)^2(j2)^2)/((j0)^2(j1)^2)]$

$NSR(3b)=10log[(2(j1)^2(j1)^3 sin^2(.5b2(\Omega2-\Omega1)^2)l)+(j1)^2(j2)^2)/((j0)^2(j1)^2)]$

$NSR(4a)=10log[(2(j1)^4 cos^2(.5(b2)(\Omega2+\Omega1)^2 l)+(j0)^2(j2)^2+(j0)^2(j3)^2*)/((j0)^2(j1)^2)]$

NSR(4b)= $10\log[((j0)^2(j2)^2+(j1)^2(j2)^2)/((j0)^2(j1)^2)]$

NSR(3c)=NSR(4c)= $10\log[((j2)^2)/((j0)^2]$

3.4.2 NON LINEAR DISTORTION IN ROF SYSTEMS USING SSB SCM

THEORY

An RoF system using SSB SCM is schematically shown in Fig . Compared to TSSB SCM, the phases of the multiplexed RF signals that drive two MZM arms are not the same as for TSSB SCM, and two subcarriers will be located on either side of the optical carrier. calculated NSR for the case of (Ω2 − Ω1) = 3 GHz, based on Table 3

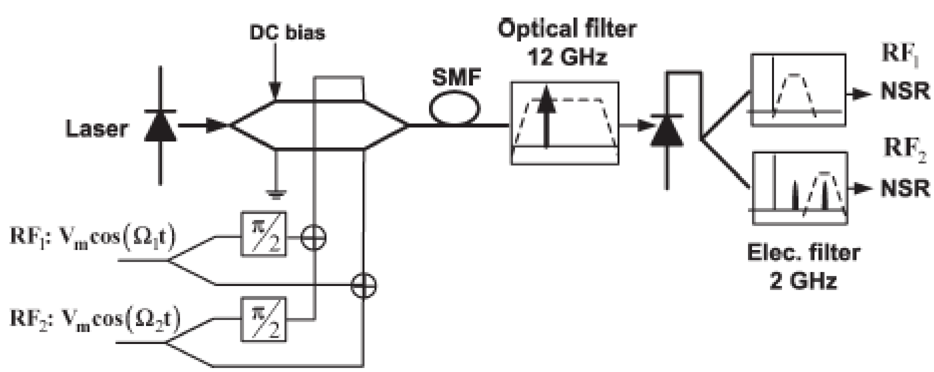

Fig 3.9 ROF system having SSB SCM [43]

We derive nonlinear distortion in an RoF system with SSB SCM using an MZM. As shown in Fig, two sets of RF signals at the frequency of Ω1 and Ω2 are applied to both electrodes of the MZM with $\pi/2$ phase shift applied to one electrode. A dc bias voltage is also applied to one electrode, while the other is grounded, biased at quadrature .When a electric field of $E_0e^{j\omega t}$, ω-optical carrier frequency is injected into the MZM

If we only consider the IMDs and HDs that may be dominant in introducing nonlinear distortion, after transmission over fibre with a length L , we get an equation as

$E_{out}= E0/2\{\sqrt{2} * (j0)2cos(w(i) * t + .25 * \pi)$

-2j0j1cos(w(i)t+Ω1(t)-b1(Ω1)l-.5b2(Ω1)(Ω1)l)

$-2j0(j1)^2cos(w(i)t+Ω2(t)-b1(Ω2)l-.5b2(Ω2)^2l)$

$+\sqrt{2}(j1)^4cos(w(i)t+(Ω2-Ω1)t-.25π-b1(Ω2-Ω1)l-.5b2$

(Ω2- Ω1)(Ω2-Ω1)l)

+√2j1j1cos(w(i)t+(Ω2-Ω1)t-.25π-b1(Ω2-Ω1)l-.5b2(Ω2-Ω1)

(Ω2-Ω1)l)

$+\sqrt{2}(j1)^2cos(w(i)t-(Ω2-Ω1)t-.25π+b1(Ω2-Ω1)l-.5b2(Ω2-Ω1)$

(Ω2-Ω1)l)

$-\sqrt{2}(j1)^2cos(w(i)t+(Ω2+Ω1)t+.25π-b1(Ω2+Ω1)l$

-.5b2(Ω2+Ω1)(Ω2+Ω1)l)

-√2j1j1cos(w(i)t-(Ω2+Ω1)t+.25π+b1(Ω2+Ω1)l

-.5b2(Ω2+Ω1)(Ω2+Ω1)l)

+√2j1j2cos(w(i)t+2Ω1t-.25π-2π9Ω1)l-2b2(Ω1)(Ω1)l)

$+\sqrt{2}j1j2cos(w(i)t-2(Ω1)t-.25π+2π(Ω1)l-2b2(Ω1)^2l)$

$+ \sqrt{2}j1j2cos(w(i)t+2(Ω2)t-.25π-2π(Ω2)l-2b2(Ω2)^2l)$

$+\sqrt{2}j1j2cos(w(i)t-2(Ω2)t-.25π+2π(Ω2)l-2b2(Ω2)^2l)$

+2j1j2cos(w(i)t-(2Ω2+Ω1)t+b1(2Ω2-Ω1)

l-.5b2(2Ω2+Ω1)(2Ω2+Ω1)l)

+2j1j2cos(w(i)t+(2Ω2-Ω1)t-b1(2Ω2-Ω1)l-.5b2(2Ω2-Ω1)

(2Ω2-Ω1)l)+2j1j2cos(w(i)t+(2Ω2+Ω1)t-b1(2Ω2+Ω1)

$$l-.5b2(2\Omega 2+\Omega 1)(2\Omega 2+\Omega 1)l)$$

$$+2j1j2\cos(w(i)t+(2\Omega 2-\Omega 1)t-b1(2\Omega 2-\Omega 1)l-.5b2(2\Omega 2-\Omega 1)(2\Omega 2-\Omega 1)l)$$

$$+2(j2)^2\cos(w(i)t+2(\Omega 2-\Omega 1)t+.25\pi-2b1(\Omega 2-\Omega 1)l-2b2(\Omega 2-\Omega 1)(\Omega 2-\Omega 1)l)$$

$$+2(j2)^2\cos(w(i)t-2(\Omega 2-\Omega 1)t+.25\pi-2b1(\Omega 2-\Omega 1)l-2b2(\Omega 2-\Omega 1)(\Omega 2-\Omega 1)l)$$

$$-2j1j3\cos(w(i)t+(3\Omega 1-\Omega 2)t-.25\pi-2b1(3\Omega 1-\Omega 2)l-.5b2(3\Omega 1-\Omega 2)(3\Omega 1-\Omega 2)l)$$

$$-2j1j3\cos(w(i)t-(3\Omega 1-\Omega 2)t-.25\pi+2b1(3\Omega 1-\Omega 2)l-.5b2(3\Omega 1-\Omega 2)(3\Omega 1-\Omega 2)l))\} \quad .....(2)$$

the first term denotes the optical carrier, the second and third terms are two USB subcarriers, and all others are either IMDs or HDs. The IMDs occur at $\pm(\Omega 2 - \Omega 1)$, $(2\Omega 2 - \Omega 1)$, $(2\Omega 1 - \Omega 2)$, $\pm(\Omega 1 + \Omega 2)$, $-(2\Omega 2 + \Omega 1)$, $-(2\Omega 1 + \Omega 2)$, $\pm 2(\Omega 2 - \Omega 1)$, $\pm(3\Omega 1 - \Omega 2)$, etc.; the HDs occur at $\pm 2\Omega 1$, $\pm 2\Omega 2$, $-3\Omega 1$, $-3\Omega 2$, etc For example, suppose that $\Omega 1 = 4$ and $\Omega 2 = 7$ GHz; thus, we have $\pm(\Omega 1 - \Omega 2) = \mp 3$, $\pm 2(\Omega 2 - \Omega 1) = \pm 6$, $\pm(\Omega 1 + \Omega 2) = \pm 11$, $2\Omega 2 - \Omega 1 = 10$, $2\Omega 1 - \Omega 2 = 1$, $\pm 2\Omega 1 = \pm 8$ GHz, and so on. For $\Omega 2 = 2\Omega 1$, and thus $\Omega 2 - \Omega 1 = \Omega 1$, the two IMDs at $\pm(\Omega 2 - \Omega 1) = \pm\Omega 1$ are overlapped with the optical signal subcarrier at $\Omega 1$, and the HD at $2\Omega 1$ is overlapped with optical signal subcarrier at $\Omega 2$ (the HD at $-2\Omega 1$ can be removed by optical filtering).

Suppose that some HDs and IMDs can be removed by optical filtering, which is assumed the same as for TSSB SCM. However, optical signal subcarriers are located in one side of the optical carrier; thus, the optical carrier for SSB SCM may not be aligned with the central wavelength of DWDM multiplexer filters. Practically, such filtering may reduce optical carrier power and thus improve the optical modulation index. However, we do not consider this filtering impact in our analysis of NSR. After photodetection, the current by use of above equation can be written as

$I = Rn(E_0)^2/2$

$$*\{((j0)^4 + 2\sqrt{2}(j0)^3(j1)\cos(\Omega1(t)-b1(\Omega1)l-.5(b2)(\Omega1)^2 l-.25\pi)$$

$$-2\sqrt{2}(j0)^3(j1)\cos(\Omega2(t)-b1(\Omega2)l-.5(b2)(\Omega2)^2 l-.25\pi)$$

$$+4(j0)^2(j1)^2\cos(.25\pi-.5(b2)(\Omega1\Omega1+\Omega1\Omega2)l)\cos((\Omega2-\Omega1)t-b1(\Omega2-\Omega1)l-$$

$$.5\, b2((\Omega2)^2 - \Omega1\Omega2)l-.25\pi)$$

$$-4(j0)^2(j1)^2\cos((\Omega2+\Omega1)t-b1(\Omega2+\Omega1)l)$$

$$+4(j0)^3(j2)\cos(2\Omega1(t)-2b1(\Omega1)l-2b2(\Omega1)^2 l-.5\pi)$$

$$+2\sqrt{2}(j0)^2 j1j2\cos((2\Omega2-\Omega1)t-b1(2\Omega2-\Omega1)l+.5b2(2\Omega2-\Omega1)(2\Omega2$$

$$-\Omega1)l+.25*\pi)$$

$$+2\sqrt{2}(j0)^2 j1j2\cos((2\Omega1-\Omega2)t-b1(2\Omega1-\Omega2)l+.5b2(2\Omega1-\Omega2)$$

$$(2\Omega1-\Omega2)l+.25\pi)$$

$$+2\sqrt{2}(j0)^2 j1j2\cos((2\Omega1+\Omega2)t-b1(2\Omega1-\Omega2)l-.5b2(2\Omega1-\Omega2)$$

$$(2\Omega1-\Omega2)l-.25\pi)$$

$$+4(j0)^2(j2)^2\cos(2(\Omega2-\Omega1)t-2b1(\Omega2-\Omega1)l-2b2(\Omega2-\Omega1)(\Omega2-\Omega1)l)$$

$$-4(j0)^2 j1j3\cos((3\Omega1-\Omega2)t-2b1(3\Omega1-\Omega2)l-.5b2(3\Omega1-\Omega2)$$

$$(3\Omega1-\Omega2)l-.25\pi)\quad)\}\qquad \ldots(3)$$

Similar to TSSB SCM, we consider three cases. NSR expressions for different combinations of Ω1 and Ω2 are listed in Table 3

Ω1 Ghz	Ω2 Ghz	Non linear distortion frequencies for Ω1	Non linear distortion frequencies for Ω2	RF Ω1 NSR	RF Ω2 NSR
1	4	2 Ω1,(Ω2-2 Ω1)	(Ω2- Ω1),(Ω2+Ω1)	NSR(5a)	NSR(6a)
2	5	(Ω2- Ω1), (Ω2-2Ω1)	2 Ω1, 2(Ω2- Ω1)	NSR(5b)	NSR(6b)
3-5	6-8	(Ω2- Ω1)	2 Ω1, 2(Ω2- Ω1)	NSR(5c)	NSR(6c)
6-7	9-10	2 (Ω2- Ω1)	(3Ω1- Ω2)	NSR(5d)	NSR(6d)

Table 3 NSR for one optical carrier having two SSB subcarriers[43]

Where

$NSR(5a) = 10\log[(2(j0)^2(j2)^2+(j1)^2(j2)^2)/((j0)^2(j1)^2)]$

$NSR(6a) = 10\log[(2(j1)^2)/((j0)^2)]$

$NSR(5b) = 10\log[(2(j1)^2\cos^2(.25\pi-.5(b2)(\Omega1)^2+(\Omega1)\Omega2)l)+(j2)^2)/((j0)^2)]$

$NSR(6b)=NSR(6c)=10\log[(2(j0)^2(j2)^2+2(j2)^4)/((j0)^2(j1)^2)]$

$NSR(5c) = 10\log[(2(j1)^2\cos^2(.25\pi-.5(b2)((\Omega1)^2+(\Omega1)(\Omega2)l))/((j0)^2)]$

$NSR(5d) = 10\log[(2(j2)^4)/((j0)^2(j1)^2)]$

$NSR(6d) = 10\log[(2(j3)^2)/((j0)^2)]$

3.5 SIMULATION RESULTS AND DISCUSSION

We have analyzed the impact of nonlinear distortion in RoF systems with TSSB and SSB SCMs, considering one wavelength carrying two RF signals. It was found that nonlinear distortion strongly depends on optical modulation index and frequency difference of the two RF signals. For a small modulation index that was widely used, TSSB and SSB SCMs induce similar and very small nonlinear distortion, and the two RF signals are not seriously distorted by nonlinear distortion. Generally speaking, NSR of below −25 dB when the frequency difference of two RF signals is ∼ 2 GHz and beyond, and −30 dB when frequency difference of two RF signals is around ∼ 1 GHz, can be obtained. However, when a medium or large modulation index is used, TSSB and SSB SCMs will induce different nonlinear distortions,[43].[47] and nonlinear distortion may be very serious. For this case, it was found that for both TSSB and SSB SCMs, NSR of below ∼ −20db can be obtained for two RF signals when a minimum RF of 3 GHz and ∼ 1-GHz frequency difference of two RF signals are used, except for the maximum modulation index. However, if the frequency difference of two RF signals is ∼ 2 GHz and beyond, NSR of below −20 dB can be only achieved using a medium optical modulation index combined with a minimum RF of 6 GHz. If a large optical modulation index is used, NSR of below −20 dB cannot be obtained for both TSSB and SSB SCMs. Moreover, as a rule of thumb for both medium and large optical modulation indexes, TSSB SCM induces a lower NSR than SSB SCM. For the case of $\Omega2 - \Omega1 = 1$ GHz, NSR for SSB SCM is almost the same as for TSSB SCM, and thus, NSR can be calculated based on Table 2. Simulation confirms that for this case NSR is almost the same.

Ω1 Ghz	Ω2 Ghz	Non linear distortion frequencies for Ω1	Non linear distortion frequencies for Ω2	RF Ω1 NSR	RF Ω2 NSR
1	4	2,2	3,3,5	- 2.1740	-5.0165
2	5	3,1	6,4,6	- 1.1638	-3.1587
4	7	3	8,6	3.7675	-3.9003
7	10	6	1,1	-8.8112	-10.4532

Table 4 values for NSR for ROF using TSSB SCM

Ω1 Ghz	Ω2 Ghz	Non linear distortion frequencies for Ω1	Non linear distortion frequencies for Ω2	RF Ω1 NSR	RF Ω2 NSR
1	2	1,2	2,3,3	- 5.2211	6.2436
2	3	1,-1	4,4	- 2.4881	-1.3140
7	8	-6	9	3.0004	-3.0004

Table 5 values for NSR for ROF using TSSB SCM with $\Omega2 - \Omega1 = 1$

Ω1 Ghz	Ω2 Ghz	Non linear distortion frequencies for Ω1	Non linear distortion frequencies for Ω2	RF Ω1 NSR	RF Ω2 NSR
1	4	2,2	3,5	- 0.1023	6.2480
2	5	3,1	4,6	- 2.3280	-1.4636
4	7	3	8,6	-0.3477	-1.4636
6	9	6	-9	-6.2282	-10.3833

Table 6 values for NSR for ROF using SSB SCM

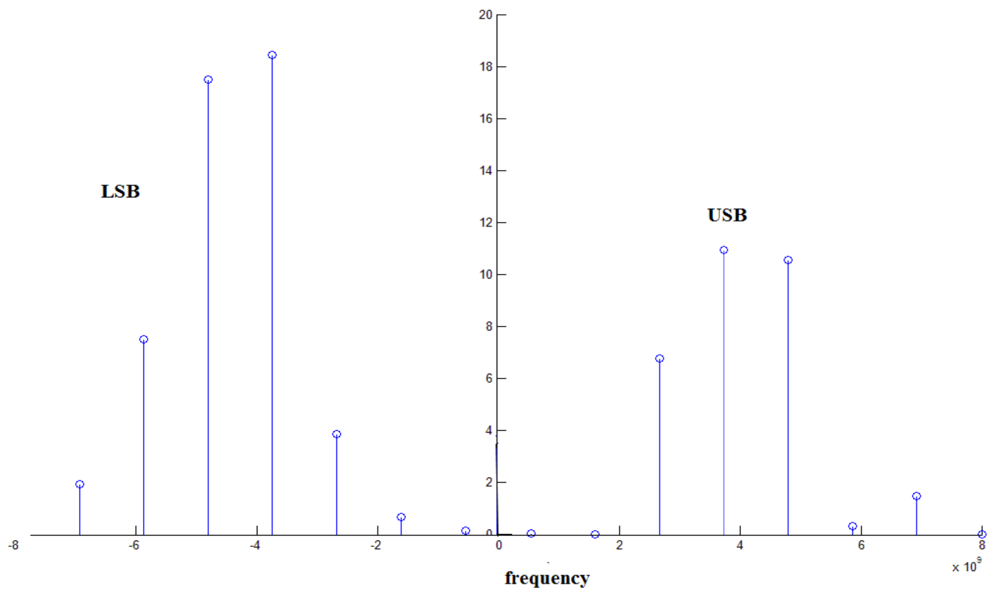

Fig 3.10 Optical spectra distribution of TSSB SCM

Fig 3.10 shows the output Optical spectra after transmission over fiber with a length of *L* corresponding to Equation 1 (page 47) where *b*1 and *b*2 denote the first and second derivatives of the propagation constant with respect to the optical carrier frequency. Some HDs and IMDs with frequency far away from the optical signal subcarriers are not shown The optical spectra of the electric field is shown in Fig. 3.10 for the case of Ω1 = 4 and Ω2 = 7 GHz

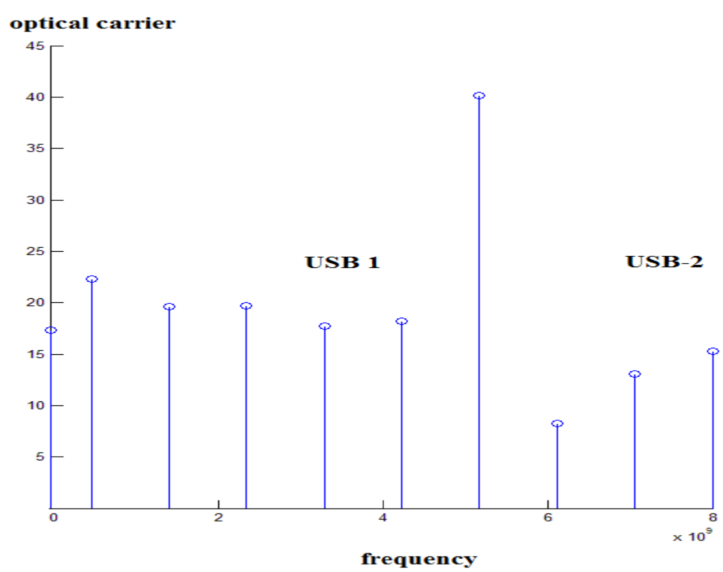

Fig 3.11 Optical Spectra distribution of SSB SCM

Fig 3.11 shows the output optical spectra after transmission over fiber with a length of *L* corresponding to Equation 2(page 53) The optical spectra corresponding is shown in Fig.3.11 for two optical subcarriers with $\Omega 1 = 4$ and $\Omega 2 = 7$ GHz. Suppose that some HDs and IMDs can be removed by optical filtering, which is assumed the same as for TSSB SCM. However, optical signal subcarriers are located in one side of the optical carrier; thus, the optical carrier for SSB SCM may not be aligned with the central wavelength of DWDM multiplexer filters.

3.6 FUTURE SCOPE OF WORK

The future scope of work involves further study of optical components and radio over fibre components for the improvement and new applications for the same.

The radio over fibre system can be used for the future wireless acess networks radio over fibre network provide bigger bandwidth and a more robust system In this dissertation, we are concerned with RoF based network architecture aimed at efficient mobility and bandwidth management using centralized control capability of the network. In particular, the focus is mainly placed on RoF networks operating at mm-wave bands. In indoor environments, the electromagnetic field at mm-wave tends to be confined by walls due to their electromagnetic properties at these frequencies. In outdoor environments, especially at frequencies around 60 GHz, an additional attenuation is necessary as oxygen absorption limits the transmission range . Both the cases result in very small cell as compared to microwave bands such as 2.4 or 5 GHz, requiring numerous BSs to be deployed to cover a broad service area. Thus, in such networks with a large number of small cells, we realize two important issues: (1) the system should be cost-effective and (2) mobility management is very significant.

One promising alternative to the first issue is an RoF based network since in this network functionally simple and cost-effective BSs are utilized in contrast to conventional wireless systems. However, the second issue is still challenging and difficult to realize as the conventional handover procedures cannot easily be applied to the system. In this dissertation, we consider first RoF network architecture operating at mm-wave bands with special emphasis on mobility management. Specifically, our concern is how to support fast and simple handover in such networks using RoF network's centralized control capability. In addition, an RoF based broadband wireless access network architecture is proposed, where wavelength division multiplexing (WDM) is utilized for bandwidth allocation. RoF systems have a wide variety of applications and they fulfill the necessary criteria for being a modern communication systems

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