Implementation of Radio Frequency Conversion Techniques for Photonic Applications

Diploma Thesis

Completed by

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STATUTORY DECLARATION

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Zusammenfassung

Die Generierung der für die im Millimeter-Wellenbereich und darüber hinaus arbeitenden Optischen Systeme mittels direkten elektronischen Methoden, ist mit hohen Kosten und Komplexität verbunden. Zur Überwindung dieser Problematik wurde die Anwendung von Photonik Techniken als Alternative intensiv untersucht. Die auf photonischen Bauelementen basierenden Freuquenzumwandlungstechniken führen zu einer Erweiterung des Frequenzbereichs, als auch der Bandbreiten für die Kommunikation und Sensor-Anwendungen.

Mit einer Übersicht der Anforderungen der optischen Kommunikationstechnik werden, nach Darstellung der aktuellen und gängig angewandten RF Up / Down Conversion, zukunftsträchtige Aspekte der Anwendung und Weiterentwicklung ausgelotet. Nach Präsentation der zukünftigen Technologie sind deren potentielle Entwicklungen als auch der Ausblick zu erwartender nachfolgender Generationen und auch generell die theoretische technische Grenze der optischen Kommunikationstechnik diskutiert.

Im Hauptkapitel werden Implementierungsmöglichkeiten für zukünftige Anwendungen behandelt als auch Optimierungen vorgeschlagen.

Abstract

For optical systems that operate at mm-wave and above, the direct method for obtaining the needed mm-wave electronically increases in costs and complexity, while frequency converter spurious and linearity performance degrades. To overcome these problems, the application of photonic techniques has been intensively investigated. Photonic conversion techniques extend the range of frequencies and bandwidth for communication and sensing applications.

Summarizing the requirements of optical communication technology, current and frequently applied RF Up / Down Conversion techniques are presented and reviewed for their promising aspects of future application and development. Presenting current technologies, their potential of future development, as well as the general theoretical technical limit of optical communications are discussed.

The main chapters gives an overview of possible implementations for future applications, as well as suggestions for optimizations.

Table of Contents

Table of Figures

1 Introduction

Communication systems transmit information as analog or digital signals that are carried at the speed of light by an electromagnetic carrier at frequencies that vary around a few megahertz to several hundred terahertz.

Since the development of the first generation of a fiber-optical communication system in the 1970s, optical communication structures have revolutionize the telecommunication industry, due to their advantages over electrical transmission. Copper wire structures have been largely substituted by optical fibers in core networks around the world.

Employing optical fibers for information transmission, relevant components have been developed only in the last forty decades, thus deploying further technological emphasis in near future.

The task of the present diploma thesis is to give an overview of the actual state of the art with regard to components and procedures on the basis of the interaction of mm-waves and light. The main focus lies on the optical radio frequency (RF) up- and down-conversion.

1.1 RF-Telecommunication

The term telecommunication refers to the transmission of information over large distances for communication purposes.

RF-Telecommunication is based on the unique properties of radio frequencies (RF - electric currents oscillating between 3 kHz and 300 GHz), not shared by direct or alternating current of lower frequencies.

The basis of radio signalling technology is that the energy in an RF current can be emitted by a conductor into free space as called ”radio waves” (electromagnetic waves).

1.1.1 Low Frequency RF-Communication

For the transmission over significant distances the use of lower band terrestrial radio signals is not advantageous, since they are extremely susceptible to atmospheric attenuation.

1.1.2 Microwave RF-Communication

Microwave RF-transmission utilizes radio waves (wavelengths in the range from 1 cm to 30 cm) to transmit information (energy) using conveniently-sized antennas in narrow beams for point-to-point communication.

In contrast to lower frequency radio waves, the short wavelength of microwave radio frequency waves permits additional microwave utensils located in close proximity to use identical frequencies without interfering with each other.

The advantage of microwaves is its band of large information-carrying capacity, with a bandwidth 30 times as large as all the remaining radio spectrum below it.

On the other hand, the disadvantage of microwaves is that they are restricted to line of sight propagation, not passing around buildings or mountains as radio waves in lower frequency bands do.

Microwave RF-communication has become obsolete in light-wave transmission due to the limited available spectrum, low data rate, high cost of bit transmission and large physical space consummation.

1.1.3 Optical RF-Communication

Optical RF-communication systems use electromagnetic light-wave carriers in the visible or near infrared spectrum (~THz), distinguishing itself by carriers range of five orders from microwave systems (~GHz).

RF-Fiber-optic communication is mainly a method of transmitting information from one place to another by sending pulses of light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated by various options to carry information.

Optical networks are the backbones of today's telecommunications systems, due to their responsiveness, as communication transport capacity has been expanding at exponential rate.

1.2 Historical Background

In broad sense of historical perspective, use of light for communication purposes dates back to antiquity (mirrors, fire bacons and signalling lamps). Messages needed about one hour for the distance of the entire 7500 km sized chinese wall length.

- 1792: Claude Chappe: mechanical coded light transmission by intermediate relay stations [2].
- 1794: First optical telegraph between Paris and Lille [2].

- 1830: Network expanded throughout Europe (effective rate of one bit per second) [1].

- 1880: Alexander Graham Bell, under assistance of Charles Sumner Tainter, build the so called “Photophone”, which is the ancestor of today’s fiber-optic communications. This apparatus enabled the world’s first wireless telephone link between two buildings (situated about 213 meters apart from each other) by the modulation of sound onto a beam of light [2].

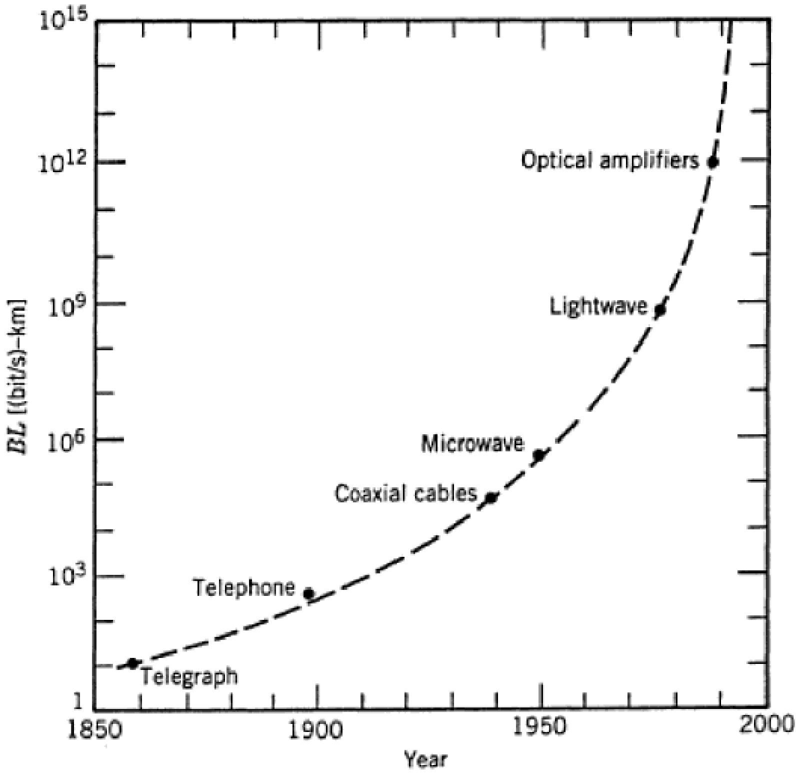


Fig. 1.1: Increase of the Bit Rate-Distance Product over the Years (taken from [1])

- 1966: Charles K. Kao and George Hockham, demonstrated that the high losses of 1000 dB/km in existing glass (compared to 5-10 dB/km in coaxial cable) arose from removable impurities in the glass, leading to their proposition of optical fibers at STC Laboratories (STL) at Harlow, England [1].

- 1975: The ***first generation*** of commercial fiber-optic communications system was developed. It operated at a wavelength around 0.8 µm at a bit rate of 45 Mbit/s with repeater spacing of up to 10 km, employing a GaAs semiconductor lasers. On the 22nd of April 1977, General Telephone and Electronics sent the first live telephone traffic through fiber optics at a 6 Mbit/s throughput in Long Beach, California [1].

- 1980s: Fiber-optics were finally deployed in telecommunication systems and the ***second generation*** of fiber-optic communication, using a InGaAsP semiconductor laser at a wavelength of 1.3 µm, was commercialized. At the end of this decade the first transatlantic telephone cable using optical fiber (TAT-8) was deployed and the ***third generation*** fiber-optic systems, operating at 1.55 µm) reduced the losses to 0.2 dB/km. This was accomplished despite earlier complications with pulse-spreading at the operating wavelength, which were finally resolved using conventional InGaAsP semiconductor lasers [2].

- 1990s: “Information Age” revolutionised by light-wave technology and microelectronics: The ***fourth generation*** of fiber-optic communication systems was introduced. To decrease the necessity for wavelength-division multiplexing and repeaters, optical amplification was employed, leading to an increase in data capacity. These two technical innovations resulted in the doubling of system capacity in a 6 months period starting in 1992 until…

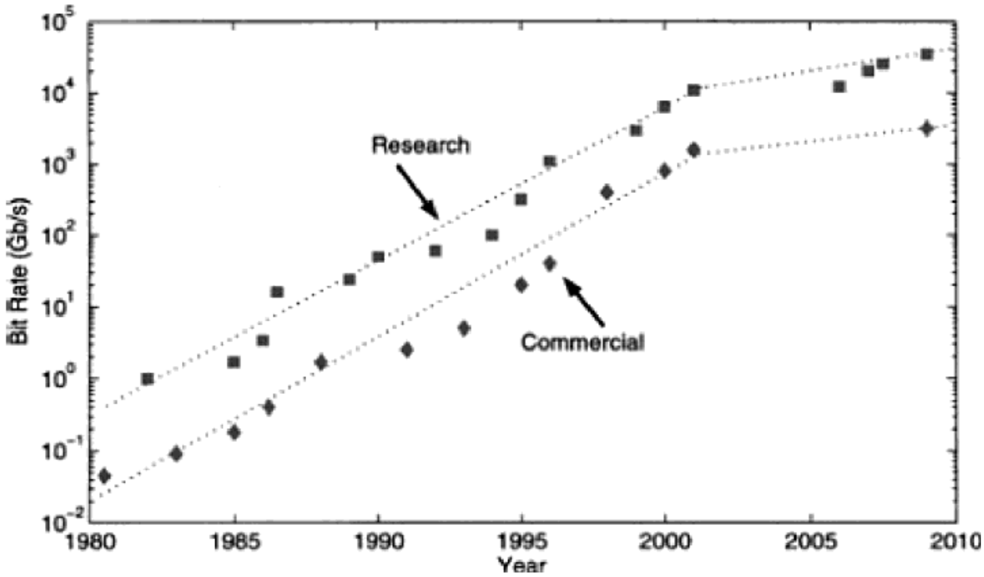


Fig. 1.2: Increase of Light-wave System Capacity over the Years (taken from [1])

- 2000s: … 10 Tbit/s were attained by 2001. Only five years later 14 Tbit/s were reached employing optical amplifiers over a single 160 km line. The ***fifth generation*** of fiber-optic communication focused on the extension of the wavelength range over which a wavelength-division multiplexing (WDM) system can run. The conventional wavelength window, known as the C band and covering the wavelength range 1.53 - 1.57 µm, could be extended to the low-loss window of dry fiber (1.30 - 1.65 µm). Other advances comprise the theory of "optical solitons" (Pulse-shape conservation by combating dispersion effects with the help of nonlinear effects produced by the fiber using specific pulse forms) [2].

- 2012: Fiber technology has become quite mature, numerous new components have appeared on the market, but have not jet completed their maturing process. WDM has evolved as the “golden standard” through further breakthroughs in light-generation, amplifying, mixing and related novel schemes, e.g. differential detection, self coherent detection (SCD) and digital coherent detection (DCD), enabling high spectral efficiency (SE) optical modulation formats supporting higher data rate [1].

The Figure below illustrates the progress of optical communication in contrast to the progress realized by electronics. In the early 90s single channel capacity reached 10 Gbit/s, then WDM was boosted by amplifying systems and enabled 40 Gbit/s per channel in 2003. Finally the 10 Tb/s margin was crossed with the aid of novel schemes in optical amplification, modulation formats and fiber design [1].

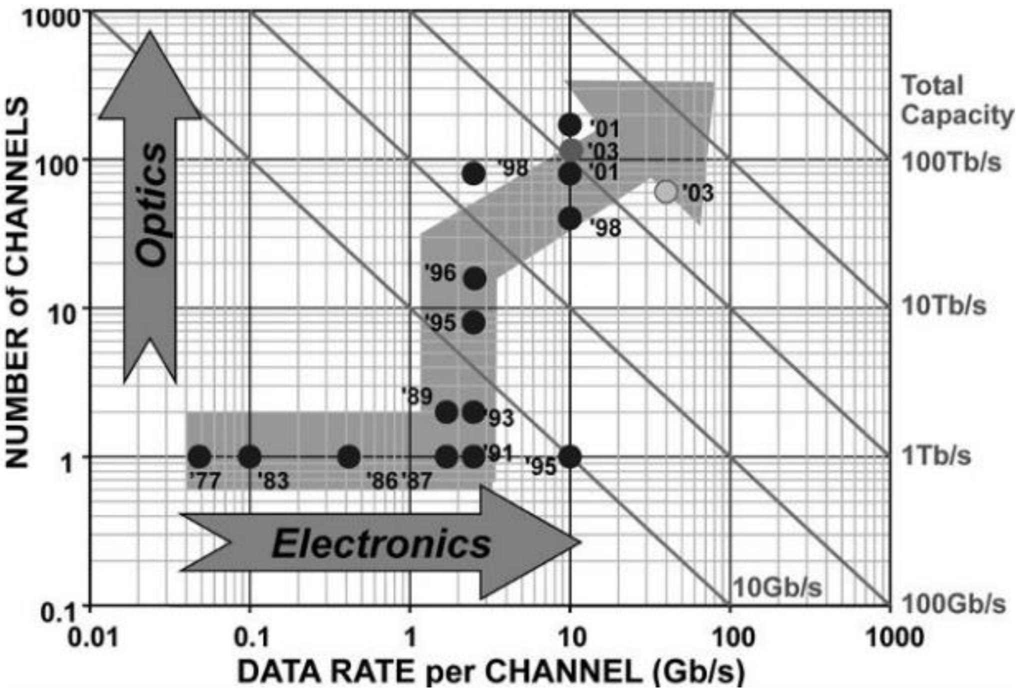


Fig. 1.3: Progress of Optical Communication versus Electronics of the first three Decades (taken from [1])

1.3 Relevant Merits of Optical Communication

Optical fiber exhibits much lower attenuation and interference than copper wire, making it beneficial for longer distances and in exigent application.

In order to select the appropriate transmission technology for a particular system a number of compromises have to be taken into account. Nevertheless, for systems that require a higher bandwidth or longer distances, the use of optical fiber is generally convenient.

The main advantages of fiber are:

- The achievement of long distances between signal amplifiers/repeaters, due to its extraordinary low loss.
- The dielectric nature of fiber optic as well as its reliance on light rather than electricity for transmission leads to the absence of ground currents and other parasite signal and power issues.
- The enormous data-carrying capacity (thousands of electrical links would be required to achieve the same capacity of a single high bandwidth fiber cable).
- No crosstalk, even when run alongside each other for long distances. Therefore fiber can be established in regions with low electromagnetic interference (EMI), for example alongside utility lines, power lines, and railroad tracks.
- Fiber-optical cables are also ideal for areas of high lightning-strike incidence.

While optical systems are able to cover distances over 100 kilometres without the use of any active or passive processing, single-line voice-grade copper systems that exceed merely a couple of kilometres already require in-line signal repeaters for acceptable performance. Single-mode fiber cables are usually available in lengths of 12 km to keep the number of required splice elements to a minimum for longer cable runs. For multi-mode fiber industrial standards mandate cable lengths of 2 km, however, they are also accessible in lengths up to 4 km [5].

For short distance and relatively low bandwidth applications, electrical transmission may be still a preferred alternative because of its lower material cost (transmitters and receivers), especially when there is no need for large quantities. Furthermore, its capability to carry electrical power as well as signals (in specially-designed cables) and ease of operating transducers in linear mode is advantageous.

Although optical communication is not frequently used in small scale systems due to the benefits of electrical transmission, they have successfully been demonstrated in small sized applications in the laboratory.

Another disadvantage of optical fibers compared to electric wires is their expensive and complicated splicing. Moreover, optical fibers are disposed to fiber fuse at higher power, which can lead to a catastrophic destruction of the fiber core and damage to other involved transmission elements.

Nevertheless, in certain situations fiber may be used even for short distance or low bandwidth applications, in particular when the communication system requires:

- No influence to electromagnetic interference and nuclear electromagnetic pulses (even though alpha and beta radiation may destroy the fiber)
- High electrical resistance – advantageous in high-voltage environments
- Smaller weight – beneficial in aviation/aerospace
- No sparks – safe to use in flammable/explosive environments
- No electromagnetic radiation and difficulties to tap – useful in high-security applications
- Smaller size – important in environments with limited space (networks, buildings, ducts, trays, …)

Beside some minor adjustments due to the small size, limited pull tension and bend radius, optical cables can be mounted using the same tools as for copper or coaxial cables. In general, optical cables can be integrated in duct systems in spans of several kilometers (depending on the duct system and installation technique). If longer cable lengths are necessary, they can be coiled at a midway point and pulled into the duct system as far as required.

2 Fundamental Aspects of Optical Communication

This chapter gives an overview of fundamental aspects that are the basis for optical communication systems.

2.1 Building Blocks

This Chapter gives an overview of the basic building blocks used in modern optical communication systems. Figure 2.1 shows the principal concept of optical interconnection (electrical signal ↔ optical carrier).

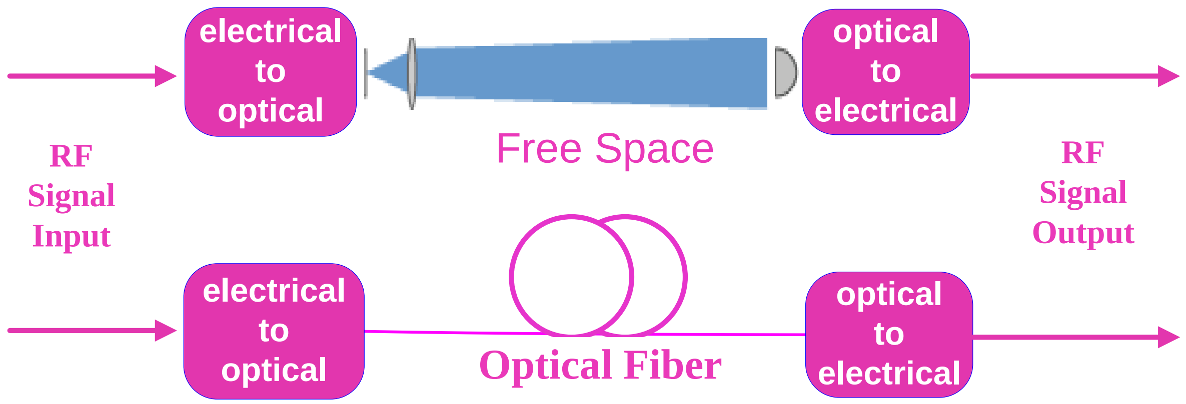


Fig. 2.1: Modules of RF Optic Communication Systems

2.1.1 Basic Concepts

The fiber-optics communication process involves the following basic steps:

- Creation of the optical signal (involving the deployment of a transmitter),
- Insertion of the optical signal into the fiber,

- Amplification/Regeneration of the optical signal to avoid distortion and attenuation,
- Reception of the optical signal, and
- Conversion of the optical signal into an electrical signal.

Before the signal can be relayed along the optical fiber, a optical transmitter is used to convert the electrical signal into the optical domain. The optical fiber encloses bundles of multiple optical fibers and is guided through underground conduits and buildings involving several different amplifiers. On the other side of the fiber an optical receiver is used to recover the signal as an electrical signal. The transmitted information is usually digital information generated with the help of computers, telephone systems, and cable television companies. In the last years the prices for fiber-optic components have dropped significantly.

2.1.2 Emitting – Up Conversion

Semiconductor devices like Laser diodes (LDs), which produce coherent light and light-emitting diodes (LEDs), producing incoherent light, are the most frequently used optical transmitters. The application of semiconductor optical transmitters in optical communications requires a compact design, efficiency and operational safety, while working precisely in an optimal wavelength range, and being directly modulated at high frequencies. The therefore required modules are illustrated in the picture below.

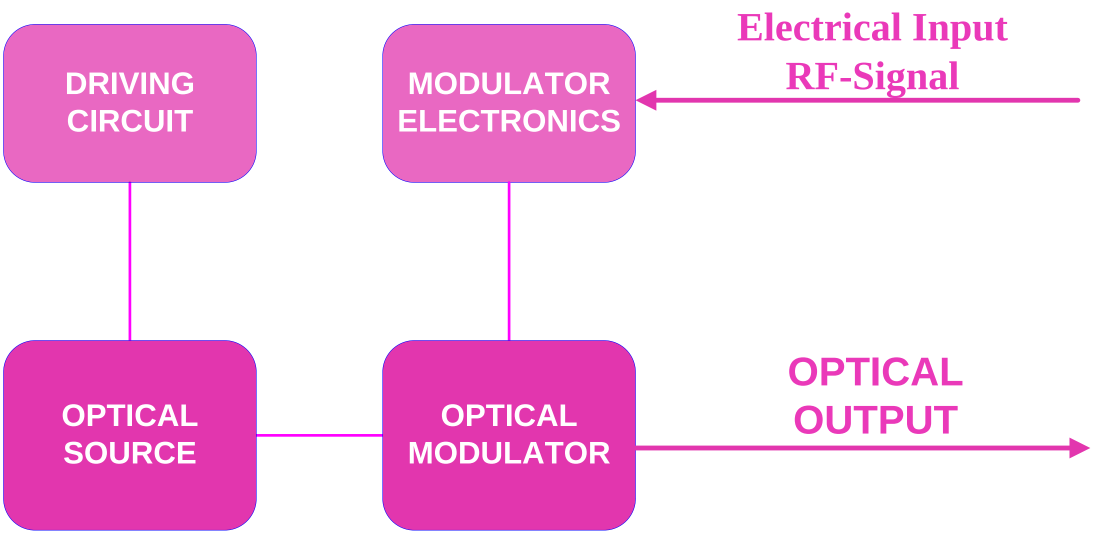


Fig. 2.2: Modules of RF Optic Signal Transmission

2.1.3 Receiving – Down Conversion

A photo detector, which is typically a semiconductor based photodiode, is the main element of an optical receiver. It converts light into electricity by means of the photoelectric effect [3]. There are several types of photodiodes including p-n photodiodes, pin photodiodes and avalanche photodiodes (can be used for particularly high sensitivity). Photo detectors, consisting of a metal-semiconductor-metal (MSM) transition are used due to their suitability for wavelength-division multiplexers and circuit integration in regenerators. The sensitivity of the receiver is limited by noise, which is normally of electronic origin. Figure 2.3 gives an overview of the therefore required modules.

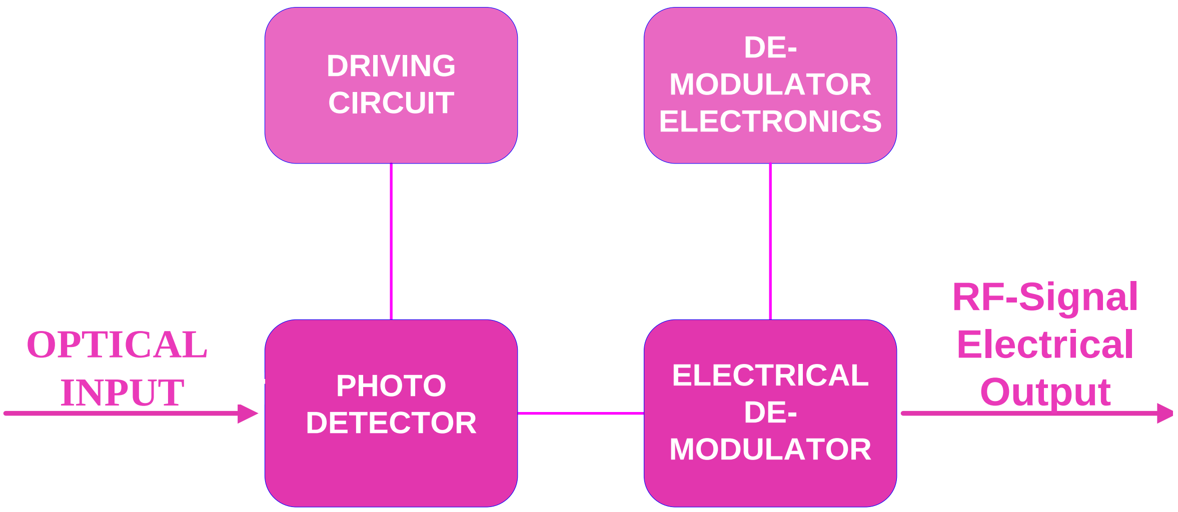


Fig. 2.3: Modules of RF Optic Signal Reception

To generate a digital signal from the received optical signal in the electrical domain, which generally subject to distortion and attenuation while passing through the channel, a limiting amplifier and a transimpedance amplifier are coupled with the O/E-converters. Additionally, before passing on the data, signal processing such as clock recovery from data (CDR) may be performed by a phase-locked loop (PLL).

2.1.4 Transceiving – Up/Down Conversion

The term “transceiver” was invented in the early 1920s. It is a device that consists of both, a transmitter and a receiver that are assembled either in a single housing or a common circuitry. When the transmit and receive functions don’t have a similar circuitry, the device is a transmitter-receiver [7].

An RF Receiver/Transmitter is (in most cases) a compact electronic device which is used for transmitting, receiving, or transceiving radio waves on one of several carrier frequencies.

Technically, transceivers must incorporate a considerable amount of the transmitter and receiver circuits. Other devices with similar characteristics are transverters, transponders, and repeaters.

2.1.5 Transmitting

2.1.5.1 Free Space

As light travels in World Space, it needs in principle no media. Light beams for point to point transmission are applicable also through our atmosphere but under the effects of related physics treating electromagnetism in dielectric media [8].

Fig. 2.4: Basic Setup for Free-Space Optical Communication

Even though the signal of the transmitter is directed in a narrow beam, there is no guarantee that 100 % of the signal power is transmitted to the detector.

It is possible to transmit tens of Mbit/s or more over many thousands of kilometers, using moderate laser average powers of the order of a few watts.

For moderate data rates and distances up to a few kilometres, simple light-emitting diodes (LEDs) can be used.

Since a major fraction of the sent power can be received (e.g. by a photodiode), the laser powers required are very modest. Subsequently, there are usually no problems regarding laser safety (especially if eye-safe lasers in the 1.5 μm spectral region are used).

However, in dielectric media, the availability of services is smaller than with a cable, because the link may be disturbed either by atmospheric influences or physical obstacles.

2.1.5.2 Optical Guiding

Transporting optical signals from source to destination, optical fibers serve as the foundation of an optical transmission system. Therefore low loss and extremely large bandwidth are essential for high speed signals over long distances, until the signal regeneration becomes indispensable.

Low-loss fiber is manufactured from several different materials: pure silica as base raw material is mixed with numerous dopants in order to modify the index of refraction according to the required needs. Two waveguide layers, the core (refractive index n_1) and the cladding (refractive index n_2) are protected by the jacket, also known as buffering coating. Although the power majority is concentrated in the core, it is likely that a minor portion spread to the cladding [1][6].

It is characterized by main parameters, such as refractive index profile ($n_1 > n_2$) and numerical aperture (NA) defining light gathering capacity:

$\max(n_0 \sin\Theta_i) = \sqrt{n_1^2 - n_2^2} \approx n_1\sqrt{2\Delta}$, when $\Delta << 1$

where Θi is the angle of incidence and Δ is normalized index difference $\Delta = (n_1 - n_2) / n_1$. Total ray deflection results when $n_0 \sin\Theta_i < \sqrt{n_1^2 - n_2^2}$ and the smallest or critical angle of incidence is equal to $\sin^{-1} n_2 / n_1$.

Micro-structured fibers may have a massive core or be hollow. In the second case, guidance therefore does not depend on refraction index or total reflection.

Guided waves in a core of air have less losses and less nonlinear effects, enabling higher optical power transfer, decreased dispersion over broad wavebands and shift to wavelengths for which material dispersion is equal to zero. Such fibers allow powerful fiber-laser operation over broad wavebands.

An optical fiber is built up of a core, a cladding, and a buffer (a protective outer coating). The cladding directs the light down the core by using the method of total internal reflection. The core and the cladding (which has a lower refractive index) are usually compounded of high-quality silica glass, although they can both be made of plastic as well. In order to connect two optical fibers with each other, they have to be spliced (fusion or mechanical splicing). This complicated procedure involves the precise alignment of the fiber cores and requires special skills and technologies.

2.1.5.3 Cable Types

Multi-mode optical fibers (MMF) and single-mode optical fibers (SMF) are the main types of optical fiber. The larger core (≥ 50 µm) of a MMF, permits less precise, cheaper transmitters and receivers to connect to it. A major disadvantage of multi-mode fibers are multimode distortion, leading to limitations of the bandwidth and length of the link. Moreover, the higher dopant content increases the price of the MMF and higher attenuation exhibits. The core of a single-mode fiber is about five times smaller than in multi-mode fiber, allowing much longer and higher performance links but requiring very expensive components and interconnection techniques [5].

The fiber is protected using a coating consisting of ultraviolet light-cured acrylate polymers. It is terminated with optical fiber connectors at both ends and finally pulled together into a cable, so that it is bundled up for commercial use. It can then be laid in the ground and run through the walls of a buildings or mounted aerially (comparable to copper cables). Once they are installed, these fibers require less maintenance than common twisted pair wires.

For long distance sub-sea data transmission (e.g. transatlantic communication cables), specialized cables are manufactured. Commercial enterprises usually have four strands of fiber enabling signals to cross the Atlantic in 60 to 70 ms.

2.1.6 Amplifiers

The limitation of the transmission distance of a fiber-optic communication system by fiber attenuation and distortion, has been solved with the use of optoelectronic repeaters: By converting the optical signal back into the electrical domain, its intensity can be significantly increased before sending it on using a transmitter. These repeaters are very expensive due to the high complexity with modern wavelength-division multiplexed signals.

As an alternative optical amplifiers can be used, which amplify the optical signal directly without converting it into an electrical signal.

The signal power level (reduced during propagation) is restored by the amplification of incident light through stimulated emission (similar procedure as for lasers but without feedback mechanism, optical gain by pumping to achieve population inversion).

For practical function ability, control and monitoring functions need to be integrated. This is done by doping a length of fiber with the rare-earth mineral erbium and pumping it with light from a laser which has a shorter wavelength (usually 980 nm) than the communications signal. Amplifiers have mostly replaced repeaters in latest installations [5][8]. They can be classified in their role of function (see Figure 2.5), such as:

- Boosters
- Preamplifiers
- Inline amplifiers

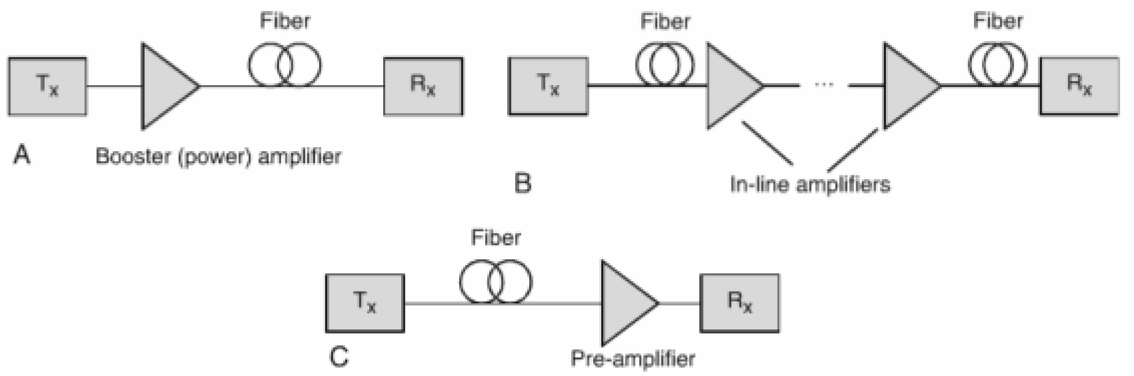


Fig. 2.5: Possible Applications of Optical Amplifiers:
(a) Booster Amplifiers, (b) In-line Amplifiers and (c) Preamplifiers (taken from [3])

Alternatively amplifiers can be classified according to their applied operation technology. Most current types are the following:

- Fiber amplifier
- Raman amplifier
- Brillouin amplifier
- Fabry-Perot amplifier (FPA)

- Traveling Wave Amplifier (TWA)
- Erbium-doped fiber amplifier (EDFA)

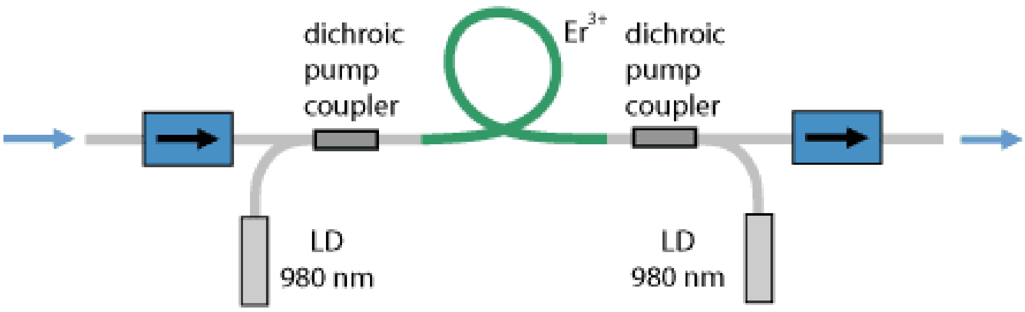


Fig. 2.6: Schematic Setup of a Simple Erbium-Doped Fiber Amplifier (taken from [10])

The most frequently used fiber amplifier deployed in long-range optical fiber communication is the erbium-doped fiber amplifier (EDFA). A typical setup of such an amplifier is shown in the picture below. EDPA amplifiers operate in the 1.5 µm wavelength region, taking advantage of the loss minimum of telecom fibers to amplify the light signal in an effective way.

The erbium-doped optical fiber constitutes the core, which is typically a SMF. The active fiber in Figure 2.6 is pumped with the light from two laser diodes (bidirectional pumping) and excites the erbium ions into a higher-energy state. The incoming signal light photons at different wavelength from the pump light meet at some point the excited erbium atoms, which give up some of their energy to the signal in form of additional photons, which are exactly at the same phase and direction as the signal light being amplifies. After that, the erbium ions return to their lower energy state. The signal light is amplified along its direction only and additional signal power is guided in the same fiber mode as the incoming signal.

The setup shown also contains two “pig-tailed” (fiber-coupled) optical isolators. The isolator at the output prevents returning reflections from the attached fiber. Such reflections disrupt amplifier operations and in the extreme case can cause the amplifier to become a laser. The isolator at the input prevents light originating from amplified spontaneous emission from disturbing any previous stages.

2.1.7 Heterodyning

An often used technique in radio signal processing is heterodyning, which is useful for frequency shifting signals into a new frequency range (up- and down-conversion), and is also involved in the process of modulation and demodulation. The input signal and a wave generated by a local oscillator are combined in a nonlinear signal-processing device, that is usually called a mixer, to create two new signals, called heterodynes or beats. While one beat has a frequency that is the sum of the mixed frequencies $f_s + f_{LO}$, the other beat has a frequency that is the difference between the mixed frequencies $f_s - f_{LO}$. Typically only one of the new frequencies is desired, and the other signal is filtered out of the output of the mixer.

The most important and widely used application on the basis of this method, is the superheterodyne detection. It is a method of detecting radiation by non-linear mixing with radiation of a reference frequency, known as the local oscillator (LO). The produced radio signal from the LO is adjusted to be close to the frequency to the incoming RF signal. After mixing, a conversion by the heterodyne technique to a lower fixed frequency signal, called the intermediate frequency (IF) takes place. This IF is amplified and filtered, before being applied to the detector, which extracts the wanted signal. The advantages of this technique are:

- The different frequencies received of different stations are all converted to the same IF frequency before amplification and filtering, so that the complicated amplifier and bandpass filter stages only have to work at one fixed frequency, the IF. This simplifies the design of the receiver.
- The IF is at a considerably lower frequency than the RF frequency of the incoming signal.

2.1.8 Mach-Zehnder Modulator

The external modulator operation is based on the linear electro-optical effect which provides a change in refractive index proportional to an applied electric field. The modulator consists of a Mach-Zehnder interferometric structure with phase modulators on each arm. The voltage applied to each arm modulates the phase of the optical carrier, so constructive and destructive interferences are obtained at the output of the modulator when this voltage is changed. The voltage-power (V-P) response for the Mach-Zehnder modulator (MZM) is given by:

$$P = \frac{P_{\max}}{2}\left[1 - \cos(\pi \frac{V}{V_\pi})\right],$$

where V is the applied voltage (bias and modulation), V_π is the half-wave voltage, and $P_{\max}$ is the maximum output power.

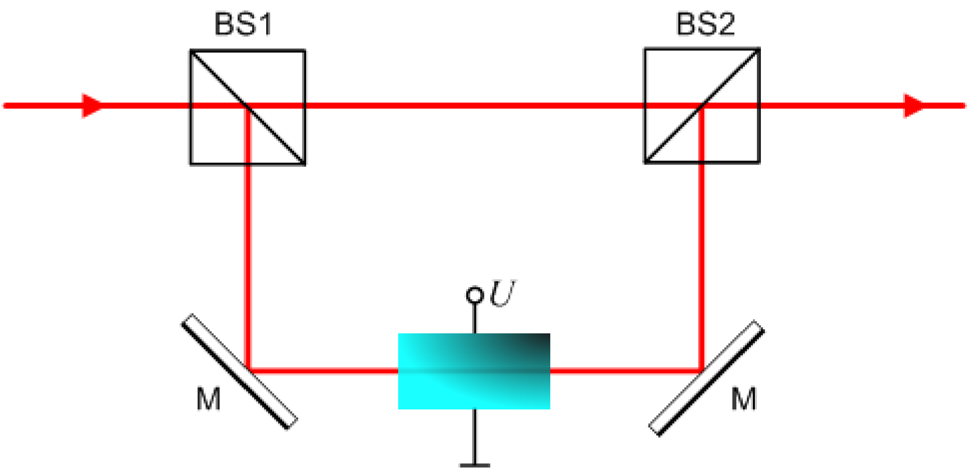


Fig. 2.7: Structure of a MZM (BS=Beam Splitter, M=Mirrors) (taken from [11])

Figure 2.7 shows the structure of a MZM. One part of the incoming light beam, that is split up by the beam splitter, is changed in its phasing with the modulation voltage and combined with the unmodified light beam by another beam splitter. Interference, that appears due to the phase shift, modulates the light beam. The applied voltage determines the phase shift and is therefore a measure for the light modulation.

MZMs for optical transmission are electro-optical modulators of Lithiumniobat (LiNbO), a titanium diffused quartz. Due to advanced technologies, their size has been minimized so that they can be inserted between the functional block of a single chip for the optical communication.

2.1.9 Other Optical Devices

Two broad categories are distinguished by operation with or without external power source:

- Active components: photodiodes, lasers, optical switches, wavelength converters external modulators
- Passive components : optical couplers, isolators, multiplexers/de-multiplexers, filters

Depending on the operational principle some may be passive or active, such as optical filters.

Optical filters are used to transmit light of a selected range of wavelengths. They are generally made up of plane glass or plastic in the optical path, which are either coloured in the mass or have interference coatings.

There are two different categories of filters: absorptive filters (simple) and interference or dichroic filters (very complex).

2.2 Relevant Engineering Issues

2.2.1 Attenuation

Fiber attenuation is caused by a combination of material absorption, Rayleigh scattering, Mie scattering, and connection losses. Even though the material absorption for pure silica leads to losses of only 0.03 dB/km (0.3 dB/km in modern fiber), impurities in the first generation optical fibers were responsible of an attenuation of about 1000 dB/km. Physical stresses to the fiber, imperfect splicing techniques and microscopic fluctuations in density can be additional sources of attenuation. Figure 2.8 lists the typical optical fiber loss related to the properties of the fiber and the applied wavelength [3].

Fiber		Optical Loss (dB/km)			
Size(µm)	Type	780 nm	850 nm	1300 nm	1550 nm
9 / 125	SM	3.0	2.5	0.5 – 0.8	0.2 – 0.4
50 / 125	MM	3.5 – 7.0	2.5 – 6.0	0.7 – 4.0	0.6 – 3.5
62.5 / 125		4.0 – 8.0	3.0 – 7.0	1.0 – 4.0	1.0 – 4.0
100 / 140		4.5 – 8.0	3.5 – 7.0	1.5 – 5.0	1.5 – 5.0
110 / 125			15		
200 / 230			12		

Fig. 2.8: Typical Fiber Loss

2.2.2 Dispersion

The maximum transmission distance is restricted by several types of dispersion or spreading of optical pulses, as they travel along the fiber. Dispersion is higher for short wave visible light. In optical fibers dispersion is induced by numerous reasons [4].

Intermodal dispersion, which is introduced by the different axial speeds of different operating transverse modes, is a limiting factor for the performance of MMF. SMF is not subject to intermodal dispersion, since there is always just a single transverse mode involved.

The performance limitation in single-mode fiber is mainly caused by chromatic dispersion, also known as group velocity dispersion. It arises because the index of the glass varies a little depending on the wavelength of the light. Due to modulation the light from real optical transmitters necessarily has nonzero spectral width.

An additional limiting factor is polarization mode dispersion, that arises due to the capability of the single-mode fiber to carry one transverse mode with two different polarizations. Distortions and minor imperfections in an optical fiber can alter the propagation velocities for the two polarizations. A countermeasure for this phenomenon, called fiber-birefringence, is the use of polarization-maintaining optical fiber.

Dispersion reduces the fiber bandwidth, because the spreading optical pulse limits the rate of sequential pulses that can still be distinguished at the receiver.

A dispersion compensator can be employed to remove the disruptive chromatic dispersion. It is realized by using a particularly prepared length of fiber with opposite dispersion to that introduced by the transmitting fiber, leading to a sharpening of the pulse with the objective that it can be correctly decoded by the electronics.

2.2.3 Bandwidth-Distance Product

The expression in unit of MHz × km is the so called bandwidth-distance product and is used to characterize the limitation of fiber transmission systems due to the gain of dispersion with the length of the fiber. The intention of this product is to point out the trade-off between signal distance and signal bandwidth. For example, a fiber characterized by bandwidth-distance product of 1000 MHz × km could either carry a 1000 MHz signal for 1 km or a 500 MHz signal for 2 km.

To improve fiber-optic communication, the ongoing reduction of current losses as well as the research for new limiting factors is fundamental.

Every single fiber is able to carry several independent channels (each using a different wavelengths), known as wavelength-division multiplexing or WDM. The net data rate (excluding overhead bytes) per fiber, is the data rate per channel (reduced by forward error correction overhead), multiplied by the channel number (typically no more than eighty in dense WDM systems). For instance, NTT was able to achieve 69.1 Tbit/s transmission by applying wavelength division multiplex (WDM) of 432 wavelengths with a capacity of 171 Gbit/s over a single 240 km long optical fiber on March 25, 2010. This was the highest optical transmission speed recorded at that time.

In intensive development NEC scientists have managed to reach speed of 101 Tbit/s by multiplexing 370 channels over single fiber, while similar Japanese effort reached 109 Tbit/s, but through a difficult production of cable with seven fibers. But this is barely matching the 50 % exponentially increasing backbone traffic.

2.2.4 Transmission Windows

The effects of attenuation and dispersion depend on the optical wavelength. For the optical transmission it is favourable to use the wavelength windows (bands) with the weakest influence of these effects. These standardized windows are currently defined as:

Band	Description	Wavelength Range
O	Original	1260 to 1360 nm
E	Extended	1360 to 1460 nm
S	short wavelengths	1460 to 1530 nm
C	conventional ("erbium window")	1530 to 1565 nm
L	long wavelengths	1565 to 1625 nm
U	ultra long wavelengths	1625 to 1675 nm

Fig. 2.9: Transmission Windows

The origin of residual absorption in low loss modern optical fibers are: Rayleigh scattering, residual infrared absorption and residual ultraviolet absorption. Hydroxyl ions (OH^-) absorb light at about 2.73 µm and to some minor extend at wavelengths of 1.39, 0.95 and 0.72 µm. The hydroxyl content must not exceed 1 ppm (part per million) so that the attenuation at 0.9 µm is below 1 dB/km.

By minimizing the water content of the fiber, there is still some residual absorption left over from the infrared absorption of the fundamental vibrations of the bonds that make up the glass. (7.3 μm for boron-oxygen bonds, 8.0 μm for phosphorous-oxygen bonds, 9.0 μm for silicon-oxygen bonds, 11.0 μm for germanium-oxygen bonds). Even at smaller wavelengths, these absorptions influence the attenuation of the fiber.

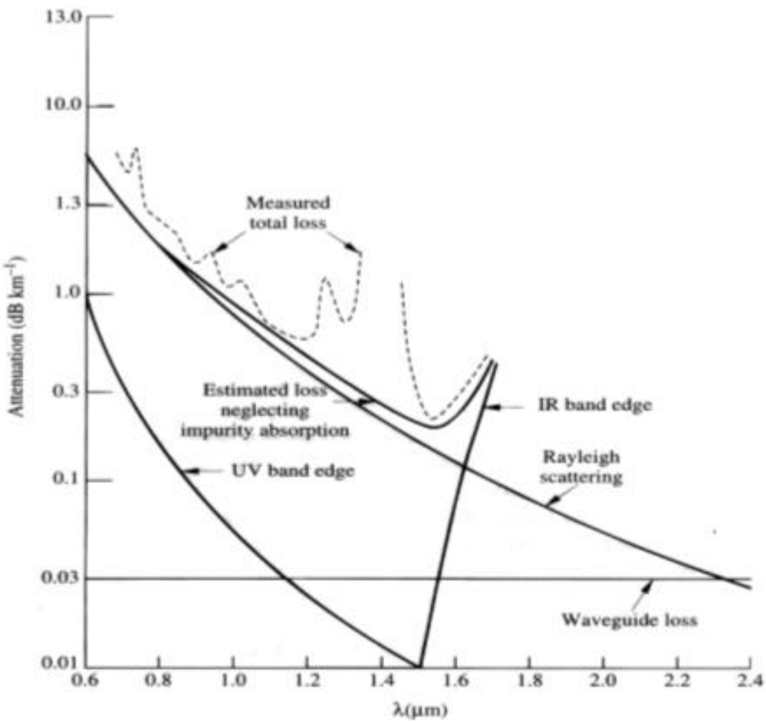


Fig. 2.10: V-Curve (taken from [14])

Rayleigh scattering, which is an inevitable source of attenuation, remains significantly in the fiber. It is defined as the natural tendency of atoms or modules to reradiate fractions of incident electromagnetic radiation omnidirectional. This phenomenom is specially remarkable at smaller wavelengths, and is boosted by the random structural properties of glass. It is also that causes for the sky to appear blue (blue light in sunlight is scattered stronger than the other colours due to its wavelength). Rayleigh scattering is enhanced by variations of the index of refraction and therefore by microscopic variations in material density of glass fiber. This loss can be minimized by drawing the fiber during production so as to minimize compositional variations.

The development of optical fiber fabrication techniques are used to decrease the effects of attenuation in modern optical fibers by eliminating impurities, in particular hydroxyl ions when the lowest attenuations are required. It should be acknowledged that the lowest levels of attenuation have been encountered at wavelengths in the near-infrared spectrum (at about 1.3 μm and 1.55 μm) and not for visible light.

Figure 2.10 and 2.11 show the variation of attenuation with wavelength of a typical modern fiber. The attenuation in the near-infrared spectrum is close to the minimal achievable values (determined by fundamental physical phenomena in the glass and not by impurities).

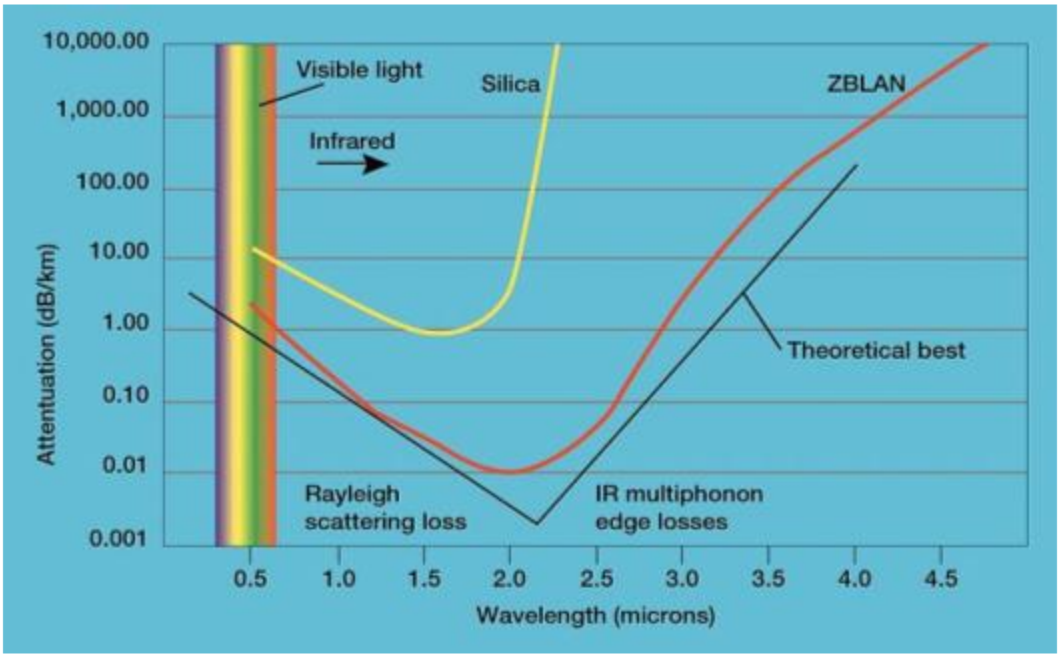


Fig. 2.11: Variation of Attenuation versus Wavelength (taken from [15])

2.2.5 Nonlinear Effects and Four-Wave Mixing

Nonlinear effects that occur in optical fibers can be split up into two general categories, as shown in Figure 2.12:

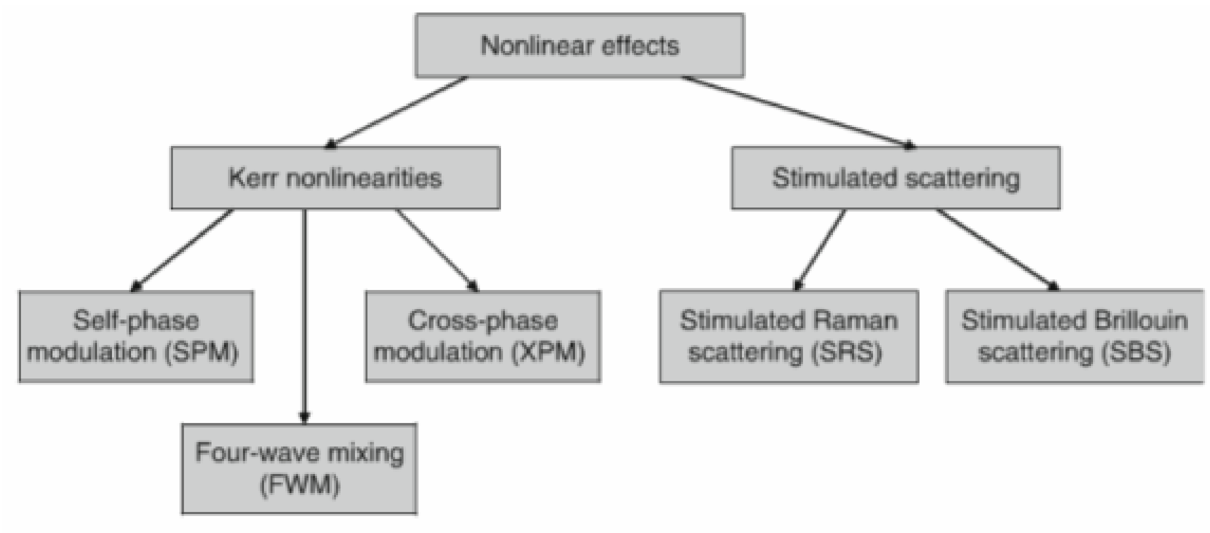


Fig. 2.12: Classification of Fiber Nonlinearities (taken from [4])

The Kerr effect which arises from modulation of the refractive index of silicia by intensity changes in the signal and leads to following nonlinearities [4]:

- Self-Phase Modulation (SPM) – an optical signal alters its own phase

- Four-Wave Mixing (FWM) – signals with different frequencies interact to produce mixing sidebands

- Cross-Phase Modulation (XPM) – one signal effects the phases of all other signals and vice-versa

The second category of nonlinearities corresponds to stimulated scattering processes, such as Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS), which are interactions between optical signals and acoustic or molecular vibrations in the fiber.

FWM has become the basis of important second-generation optical devices and optical device measurement technology, but is to be avoided in the transmission of dense wavelength-division multiplexed (DWDM) signals. As described above, it is a type of optical Kerr effect, that occurs when light of three different wavelengths is launched into the fiber, giving rise to a new wave that is known as an "idler".

Figure 2.13 is a schematic diagram that shows four-wave mixing in the frequency domain, where the probe light (signal light) is the light that was there before launching.

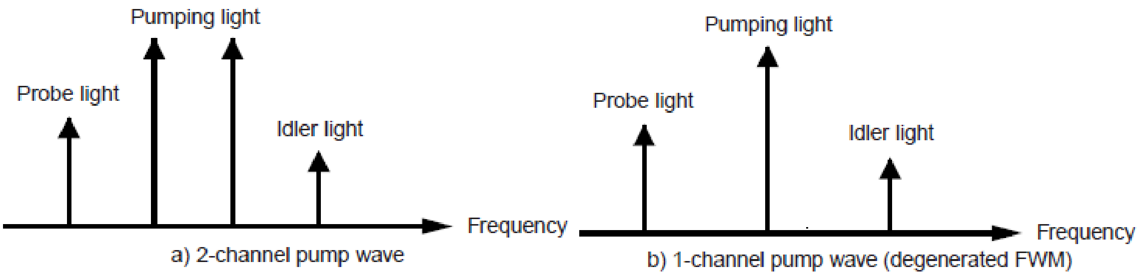


Fig. 2.13: Four-Wave Mixing in the Frequency Domain (taken from [13])

When the idler frequency f_{idler} is determined by $f_{idler} = f_{p1} + f_{p2} - f_{probe}$, where f_{p1} and f_{p2} are the pumping light frequencies and f_{probe} is the frequency of the probe light, we speak of the-matching condition. While the more specific term "degenerate four-wave mixing" is used, when the two pumping waves are identical. Therefore, $f_{idler} = 2f_p - f_{probe}$, where f_p is the frequency of the degenerated pumping wave.

Four-wave mixing is a phase-sensitive process, which means that the interaction depends on the relative phases of all beams. The effect of four-wave mixing can add up over longer distances in an efficient way, for example in a fiber only if a phase-matching condition is satisfied. This is nearly the case, if the frequencies involved are close to each other, or if the chromatic dispersion profile has a suitable shape. If there is a strong phase mismatch, four-wave mixing is effectively suppressed. In bulk media, by using appropriate angles between the beams, phase matching may also be achieved.

FWM is relevant in a numerous situations:

- Fiber-based optical parametric amplifiers (OPAs) and oscillators (OPOs) use the principle of FWM. In contrast to OPOs and OPAs based on a second order nonlinear medium, such fiber-based devices have a pump frequency between that of signal and idler.

- It can be implicated in strong spectral broadening in fiber amplifiers (e.g. nanosecond pulses).
- The harmful cross-talk effect between different wavelength channels, and/or an imbalance of channel powers can appear on the basis of wavelength division multiplexing with the use of FWM in optical fiber communication. One way to suppress this is avoiding an equidistant channel spacing.
- FWM can also be applied for phase conjugation, holographic imaging, and optical image processing.

2.3 Modulation Formats

The mainly digital transmission that makes the system multifunctional and relatively insensitive to nonlinear distortions, can be realized with different modulation formats.

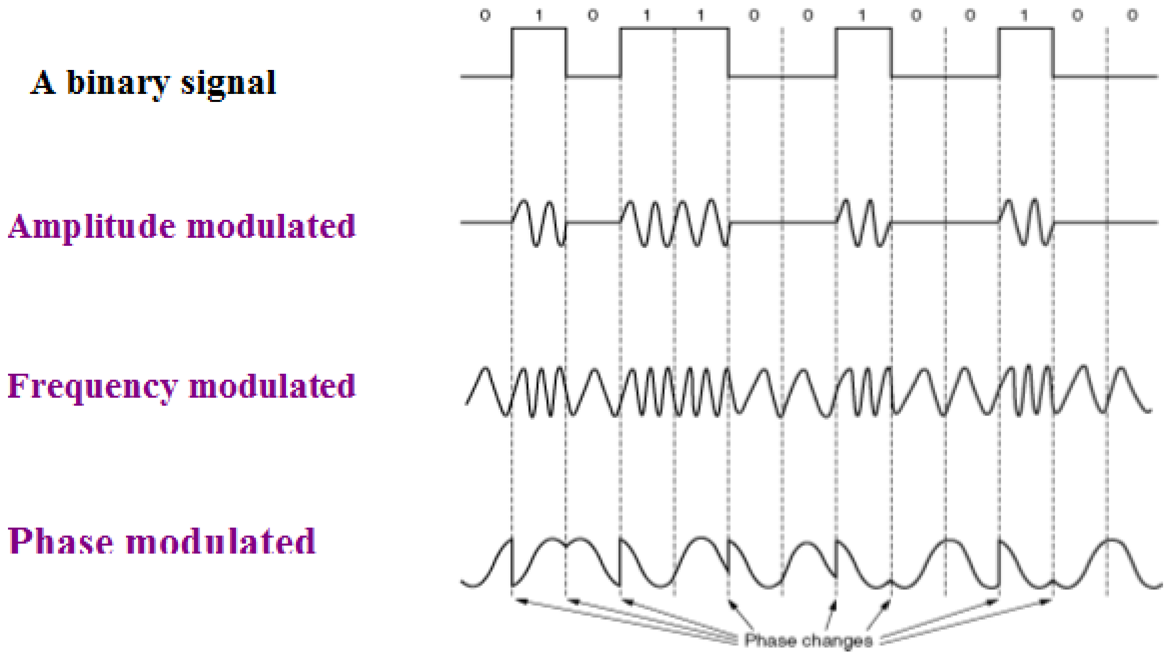


Fig. 2.14: Modulation Formats

2.3.1 Time Multiplexing (TM)

Signals of different channels are interleaved in the time domain forming a composite bit stream.

2.3.2 Channel Multiplexing (CM)

With the use of channel multiplexing a single transmission path is divided into several parts that can transfer multiple communication channels (voice/data). Multiplexing may be accomplished by frequency division (dividing into frequency bands), time division (dividing into time slots), code division (dividing into coded data that randomly overlap), or statistical multiplexing (dynamically assigning portions of channels when activity exists)

2.3.3 Frequency Division Multiplexing (FDM)

Frequency-division multiplexing is an analog technology, which realizes the grouping of a number of digital signals into one medium by sending signals in several discrete frequency ranges over that medium.

The most familiar applications of frequency division multiplexing is cable television. Even though only one cable arrives at a subscriber's home, the cable service provider can send several different television channels or signals at the same time over that cable to all customers. To access the desired channel, receivers must tune to the suitable frequency.

2.3.3.1 Orthogonal FDM (OFDM)

Orthogonal frequency division multiplexing encodes digital data on several different carrier frequencies and is a very popular scheme for wideband digital communication systems (wireless and over copper wires) [3][4]. It is employed in:

- Digital television and audio broadcasting
- 4G mobile communications
- DSL broadband internet access, and
- Wireless networks.

OFDM is a frequency-division multiplexing (FDM) scheme used as a digital multi-carrier modulation method. To carry data a large amount of closely spaced orthogonal sub-carrier signals are used, each transmitting a fractional amount of the initial data streams (serial to parallel converter). With modulation schemes like quadrature amplitude modulation (QAM) or phase-shift keying (PSK), each sub-carrier is modulated at a low symbol rate, sustaining total data rates in the same bandwidth as single-carrier modulation formats.

One of the most favourable properties of OFDM over single-carrier schemes is its capability to operate under severe channel conditions without using complex equalization filters. OFDM can be seen as collection of slowly modulated narrowband signals rather than one rapidly modulated wideband signal, which leads to a simplification of the channel equalization. The use of a guard interval between symbols is affordable, due to the low symbol rate, permitting the removal of intersymbol interference (ISI) as well as employing echoes and time-spreading to accomplish a diversity gain (improvement of the signal-to-noise ratio).

2.3.3.2 OFDM extended with Multiple Access

Orthogonal frequency division multiplexing is a digital modulation technique, which transfers one bit stream over a single communication channel (no method for multi-user channel access) using one sequence of OFDM symbols. With the use of frequency, coding and time separations, OFDM can be combined with multiple access.

In OFDMA, frequency-division multiple access is realized by the assignment of different OFDM sub-carriers to different users. The quality can be varied by assigning different number of sub-channels to different users.

OFDMA is used in…

- …the mobility mode of the IEEE 802.16 Wireless MAN standard, better known as WiMAX,
- …the IEEE 802.20 mobile Wireless MAN standard, commonly referred to as MBWA,
- …the 3GPP Long Term Evolution (LTE) fourth generation mobile broadband standard downlink. The radio interface was formerly named High Speed OFDM Packet Access (HSOPA), now named Evolved UMTS Terrestrial Radio Access (E-UTRA).
- …the now defunct Qualcomm/3GPP2 Ultra Mobile Broadband (UMB) project, intended as a successor of CDMA2000, but replaced by LTE.

OFDMA is also a candidate access method for the IEEE 802.22 Wireless Regional Area Networks (WRAN). The aim of the project is to design the first cognitive radio based standard operating in the VHF-low UHF spectrum (TV spectrum).

2.3.4 Wavelength-Division Multiplexing (WDM)

Wavelength-division multiplexing multiplies the available capacity of optical fibers by the means of parallel channels usage, where each channel is on a dedicated wavelength of light (Figure 2.15). Consequently a wavelength division multiplexer in the transmitting equipment and a de-multiplexer (essentially a spectrometer) in the receiving equipment are required [6].

Arrayed waveguide gratings are generally used for multiplexing and de-multiplexing in wavelength division multiplexing. With the help of commercial WDM systems the bandwidth of a fiber can be divided in up to 160 channels leading to a overall bit rate in the Tbit/s range. Optical amplifiers instead of regenerators allow parallel amplification of channels at distances of 60 to 120 km.

Modern WDM systems employ advanced modulation formats in which information is encoded using as well amplitude and phase of the optical carrier. Advanced modulation formats (e.g. DPSK, QPSK, QAM) are increasingly being used in order to improve the spectral efficiency of WDM light-wave systems.

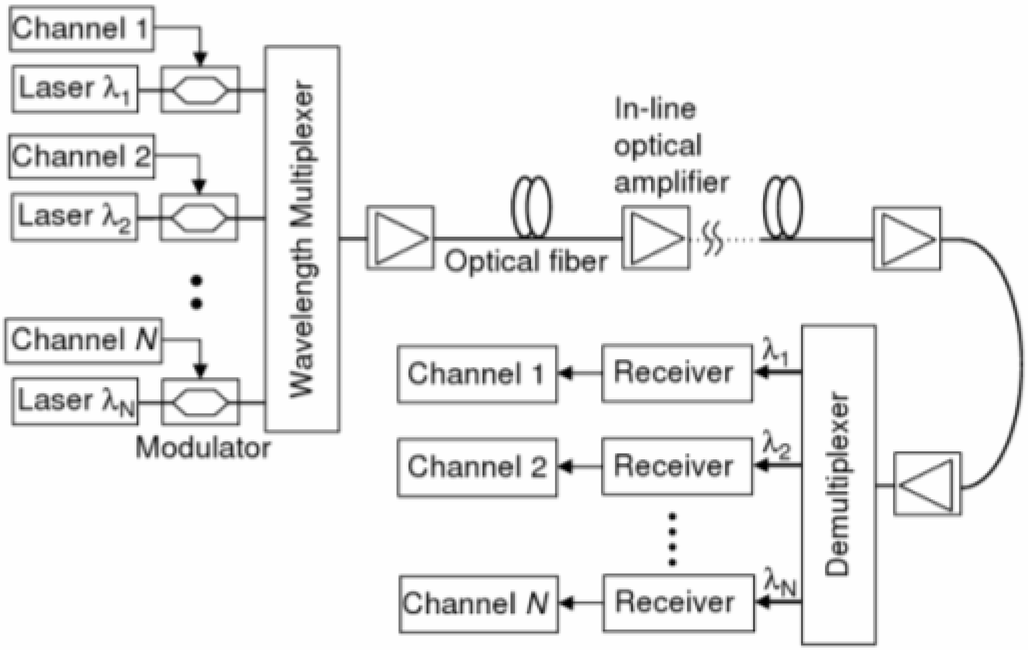


Fig. 2.15: Block Diagram of a WDM Optical System using External Modulation (taken from [6])

The Dense Wavelength Division Multiplex (DWDM) is presently known as the most powerful version. The spectral wavelengths, used for the transmission over the optical fiber cable, are very close together. The frequency range of the wavelengths, lies usually in the C-or L-band with a frequency spacing of 0.4 nm (50 GHz) to 1.6 nm (200 GHz). These short frequency spacings can only be accomplished with the use of temperature- and wavelength stabilized laser (DFB laser diodes thermostated), as well as high quality filters. Data rates of 10-100 Gbit/s per channel with up to 80 channels can be obtained. By combining the C-and L-band, up to 160 channels are available.

Depending on the manufacturer, network design and fiber type, optical amplifiers are required every 80-200 km, as well as electrical data recovery every 600-2000 km. For this reason, this technology is mainly used for long distances in a Wide- and Global Area Network. The higher the data rate on a channel, the more interferences by dispersion can occur. At data rates of 10 Gbit/s influences by chromatic dispersion must be taken into account, whereas at data rates up to 40 Gbit/s give rise to other non-linear effects, such as polarization mode dispersion (PMD).

2.3.5 Cross-Phase Modulation (XPM)

Cross-phase modulation is a nonlinear optical effect that appears when one wavelength of light is affected by the phase of another wavelength of light due to the optical Kerr effect: a technique for modulating information onto a stream of light by phase modification of a coherent optical beam with another beam through interactions in an appropriate non-linear medium (phase length conversion).

Advantages of XPM:

- Nonlinear Pulse Compression
- Passive mode locking
- Ultra fast optical switching
- De-multiplexing of OTDM channels
- Wavelength conversion of WDM channels

Disadvantages of XPM:

- Interchannel crosstalk in optical fiber communication systems
- Introduction of amplitude and timing jitter

2.3.6 Other Specific Modulating Techniques

2.3.6.1 SPM Self Phase Modulation

Self-phase modulation is another nonlinear optical effect, where an optical signal alters in its own phase, due to the optical Kerr effect. The Kerr effect induces a varying refractive index of the medium, when a ultra short pulse light is launched in a medium, producing a phase shift in the pulse and leading to a change of the pulse's frequency spectrum.

SPM is an significant phenomena in optical communication systems that use short pulses of light with high intensity, such as lasers and optical fiber communications systems.

2.3.6.2 SPM Signal Distortions and SPM Optical Pulse Processing Techniques

A couple of applications in the field of ultra short pulse have been stimulated by self-phase modulation, among others:

- Spectral broadening and supercontinuum
- Temporal pulse compression
- Spectral pulse compression

For several optical pulse processing techniques the nonlinear properties of the Kerr effect have also been advantageous (optical regeneration, wavelength conversion,…). Attenuation strategies in DWDM systems in long-haul single-channel and DWDM systems self-phase modulation is one of the most important reach limiting nonlinear effects and can be reduced by:

- Decreasing the optical power at the expense of increased noise
- Dispersion management, because dispersion can partly mitigate the SPM effect

2.4 Transmission System Performance Assessment

2.4.1 System Design

To comply with the system design task, high grade of interdisciplinary knowledge in respect to specific topics is actually required and mathematic formulas for physics of key components and telecommunication theory are a prerequisite.

Typical data of optical parameters for different optical components (product data sheet – catalogues – engineering sourcebooks) are the numerical inputs to be used for system design and last but not least in cost calculations.

Selection of components in the relevant analysis of transmission penalties and trade offs for the design engineering goals must therefore be achieved from several different aspects.

The system engineering process mainly focuses on:

- Power budget or the difference of emitted to received power level and
- Assessments of limitations of bandwidth transmission for key parameters defining signal quality

Main key steps are:

- Establishing practical reference points with respect to the impact of impairments and to signal quality,
- Optimising system characteristics by fine tuning of some parameters, whereas some of minor impact to transmission characteristics may at given scenarios be neglected.

The role of engineers is to calculate, adjust, select the system parameters and the components involved in the system.

2.4.2 Measurement Techniques

Not to aboard by technical details for this subject in this context, it is referred to ample specialised literature and numerous practical treatises.

Therefore only main parameters are listed that need to be measured after design for optimal adjustments and as well as during operation as control monitoring and error indication :

- Loss budget
- Link budget (worst case approach)
- Various types of noise sources due to connection, splices, attenuation, dispersion, etc.
- Signal quality and bit error
- Signal to noise ratio (SNR) for analog and
- Bit error rate (BER) for digital transmission
- Upper and lower power window of operation
- Modulation error ratio (MER)
- Intermodulation distortion error (IMD) caused by fiber non linearity
- Spurious free dynamic range (SFDR), maximum dynamic range

Increasing power level to overcome attenuation is limited by constraints as maximum optical power (laser safety) and limits of receiver sensitivity (saturation). Most noise sources are independent of power level. Noise floor is limiting link performance.

2.4.3 Performance Monitoring

Several possible figures of merit to be used to characterise system performance of power budget or difference of emitted to received power levels.

2.4.4 Standards

In the last years numerous standards have been developed for manufacturers, aiming the development of compatibly fiber optic communication systems, including their components. The International Telecommunications Union publishes quite a few standards, which are related to the performance and characteristics of fibers, among others [8]:

- ITU-T G.651, “Characteristics of a 50/125 µm multimode graded index optical fiber cable”
- ITU-T G.652, “Characteristics of a single-mode optical fiber cable”

Additional standards specify performance measures for the combined usage of fiber technology with devices like transmitters and receivers in order to incorporate these components to form increasingly perwerful systems. Examples for these standards are:

- 100 Gigabit Ethernet
- 10 Gigabit Ethernet

- Fiber Channel
- Gigabit Ethernet
- HIPPI
- Synchronous Digital Hierarchy
- Synchronous Optical Networking
- Optical Transport Network (OTN)

One of the most common format for digital audio cable using plastic optical fiber to connect digital sources to digital receivers is TOSLINK.

3 Standard Photonic RF Up- and Down-Conversion Techniques

The present study mainly focuses on components regarding optical RF up- and down-conversion.

3.1 Task Positioning

Since RF-Microwave communication preceded light-wave transmission, also developers were forced to switch their field of activity in order to evade the restriction with respect to limited available spectrum, low data rate copper cable, high cost of bit transmission and large physical space consumption.

Optical fibers are now the standard technology with a transmission capacity per fiber, ranging from several hundreds of Gbit/s up to Tbit/s. The throughput of deployed cables can be increased by two orders of magnitude within the currently developed spectral band by combination of increased DWDM, or more wavelength per fiber and higher data rate modulation.

In the first decade of the 2000 spectral bandwidth expanded by tenfold, beyond 2010 new fibers will extend the low loss spectrum by hundreds of nanometres.

Except fiber, many other new components for optic communication have entered the market only in 2001 and many are in conception and under development.

DWDM where information is encoded using as well amplitude and phase of carrier in the spectral range of above 8 bits/s/Hz, so that with more than 500 channels 60 Tbit/s is exceeded. Channel spacing of about 12,5 GHz.

For optical systems (Figure 3.1) that operate at mm-wave and above, the direct method for obtaining the needed mm-wave electronically increases in costs and complexity, while frequency converter spurious and linearity performance degrades. To overcome these problems, the application of photonic techniques has been intensively investigated. Photonic conversion techniques extend the range of frequencies and bandwidth for communication and sensing applications. The following chapter gives an overview of the latest methods of photonic RF conversion techniques as well as a down-conversion detection method, followed by the latest implications of this technology.

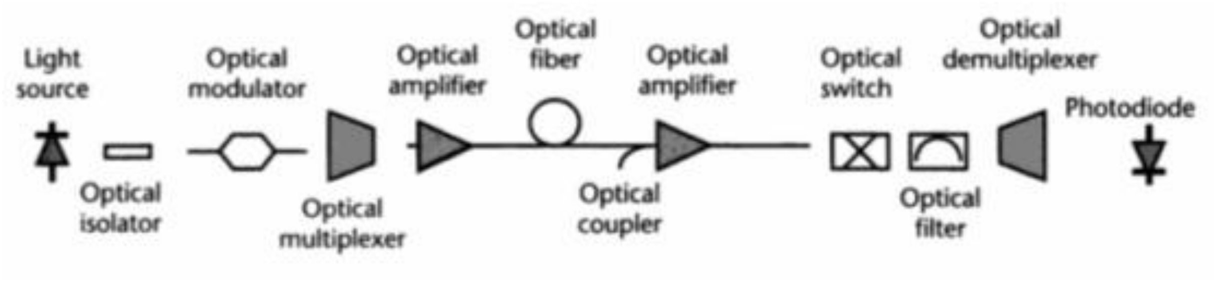


Fig. 3.1: Optical Components and their likely Position along the Light-Wave Path (taken from [7])

3.2 Nondegenerate Four-Wave-Mixing-Based RF Up- and Down-Conversion using a Parametric Loop Mirror

Figure 3.2 and 3.3 show the basic configuration of the parametric loop (PALM), which consists of a nonlinear FWM medium and a dispersive element, connected by a 3-dB coupler to create a Sagnac interferometer loop [16].

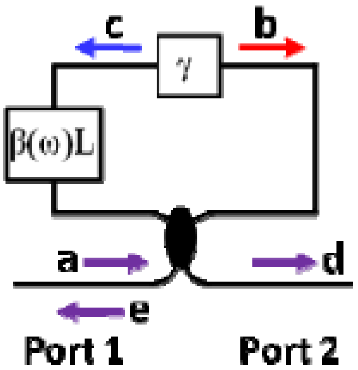


Fig. 3.2: Configuration of a PALM (γ : Nonlinear element, $\beta(\omega)L$: Dispersion element) (taken from [16])

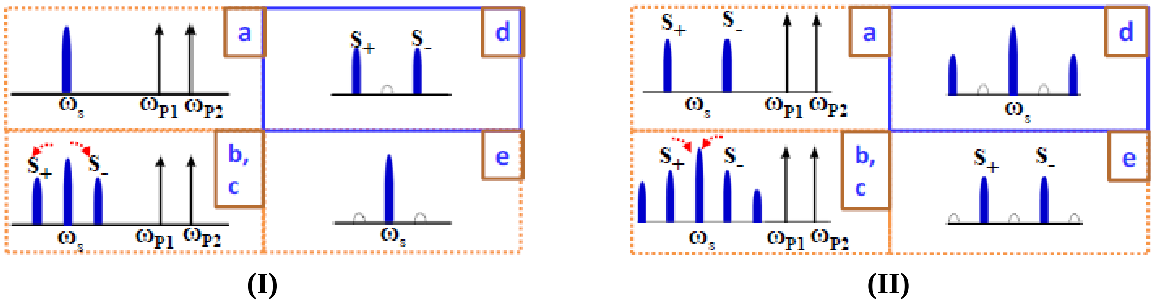


Fig. 3.3: (I) Principle of Up Conversion and (II) Principle of Down Conversion (Blocks a to e correspond to the points of a to e in Fig. 3.2) (taken from [16])

The principle of the up-conversion is shown in Figure 3.3-I a: One signal (ω_s) and two pump waves (ω_{P1} and ω_{P2}) are injected into the loop from port 1, where a 3 dB optical coupler splits them into two equal copies. After bidirectional propagation through a nonlinear element and a dispersive element, the nondegenerate FWM among the pumps and the signal generate two idlers, S_+ and S_-, with frequencies of $\omega_s \pm \Delta\omega$, where $\Delta\omega = \omega_{P1} - \omega_{P2}$ is the frequency between the two pumps (Figure 3.3-I b and c). Each idler has two copies that propagate reversely in the loop. A certain phase difference between those two copies is intentionally induced by the dispersion element when they reach the optical coupler again. This phase difference determines the output power of the idlers from port 2 by:

$$P_{port2} = P_{idler} \frac{1 - \cos \Delta\phi}{2},$$

where $\Delta\phi = \Delta\beta L$ is the phase difference, $\Delta\beta$ is the propagating constant difference in the dispersion element for the two copies of idler propagating reversely in the loop, and L is the length of the dispersion element. For idler S_+, $\Delta\beta$ can be expressed as:

$$\Delta\beta_{S+} = \beta(\omega_S + \omega_{P1} - \omega_{P2}) - [\beta(\omega_S) + \beta(\omega_{P1}) - \beta(\omega_{P2})].$$

For idler S_-, $\Delta\beta$ is similarly written as:

$$\Delta\beta_{S+} = \beta(\omega_S - \omega_{P1} + \omega_{P2}) - [\beta(\omega_S) - \beta(\omega_{P1}) + \beta(\omega_{P2})],$$

where $\beta(*)$ indicates the propagating constant in the dispersion element at each frequency. By carefully controlling $\Delta\phi$, the newly generated idlers can only come out from port 2 (Figure 3.4 d).

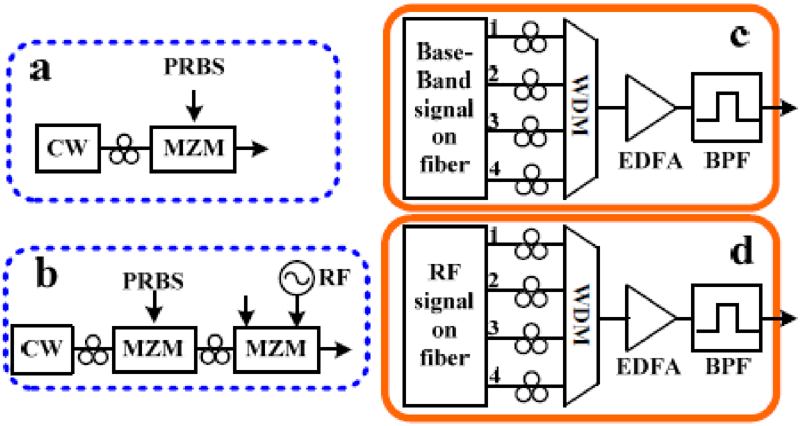


Fig. 3.4: Experimental Setup 1: (a) Setup for generating Baseband Signal, (b) Setup for simulating ROF Signal, (c) WDM Baseband Signal over Fiber to be Up-converted and (d) WDM ROF Signal to be Down-converted (taken from [16])

On the other hand, no phase difference is induced between two copies of the signals so that they only come out from port 1 (Figure 3.3-I e). As a result, both idlers (S_+ and S_-) are separated from the original input signal. If the two pumps are phase coherent, both idlers are phase coherent, resulting in a stable RF Signal with a frequency of $\omega_{S+} - \omega_{S-} = 2\Delta\omega$ after O/E conversion from a baseband to a RF Signal can be realized without the use of a notch filter to suppress the original optical carrier. Similarly, when a carrier-suppressed (CS) radio-over-fiber (RoF) signal is input into the proposed setup, both upper and lower sidebands generate an idler at the frequency ω_s (Figure 3.3-II b and c). The idlers overlap with each other and come out of port 2 (Figure 3.3-II d), while the two sidebands still come out from port 1 (Figure 3.3 II e). Therefore, the CS-RoF signal is down converted to the original optical carrier.

The PALM with a 400 m highly nonlinear fiber (HNLF) and a 1 km single-mode-fiber (SMF) serving as a nonlinear element and a dispersion element are the main elements of the up/down conversion of the experimental setup shown in Figures 3.4 and 3.5.

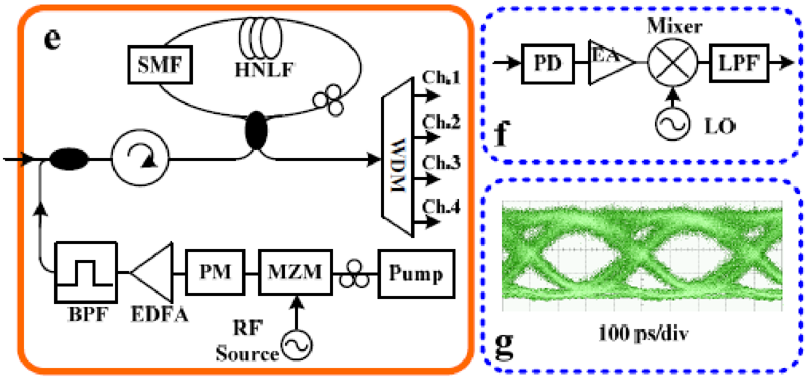


Fig. 3.5: Experimental Setup 2: (e) Optical Up/Down Converter, (f) Setup for ROF Signal Demodulation and (g) Demodulated Eye-Diagram using Setup f (taken from [16])

The Mach-Zehnder modulator (MZM), which modulates a laser at 1559 nm, operates at the zero-transmission point and is driven by an RF source with a frequency of f_0 (5-15 Ghz) to generate two phase-coherent sidebands with the frequency spacing of $2f_0$. A phase modulator is driven by pseudo random bit sequence with repetition rate of $f_0/2$ and serves for the pump spectrum broadening in order to suppress the stimulated Brillouin scattering. This phase modulation does no harm to the up converted signal because they cancel each other out during the none degenerate four-wave-mixing process.

Figure 3.4 a shows the setup for generating the baseband signal with the use of a intensity modulator which is driven by pseudo random bit sequence with repetition rate of $f_0/2$. With the use of a erbium-doped fiber amplifier (EDFA), the pumps and the signal are amplified around 14 dBm and 8 dBm, before being coupled into the PALM.

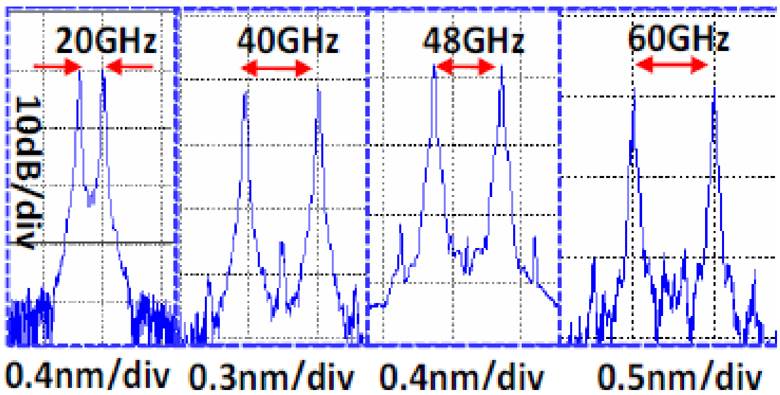


Fig. 3.6: Optical Spectrum of the Up-converted Signals (Baseband Signal is Up-converted to 20, 40 and 60GHz (taken from [16])

Figure 3.5 f illustrates the setup for the demodulation of the up-converted signal of 2.5 Gbit/s NRZ at 20 GHz carrier in the electrical domain, to demonstrate the effectiveness of the proposed method. A photo-detector with 50 GHz bandwidth is used for the detection of the output signal from the loop. This signal is RF amplified and mixed with a 20 GHz local oscillator. After 5 GHz low-pass filtering, the signal is demodulated. With two MZMs the upcoming CS-RoF is generated for the down-conversion, as shown in Figure 3.4 b. The first MZM is used to load the 2.5 Gbit/s pseudo random bit sequence data and the second one is biased at V_π and is driven by a 20 GHz RF clock to realize optical CS.

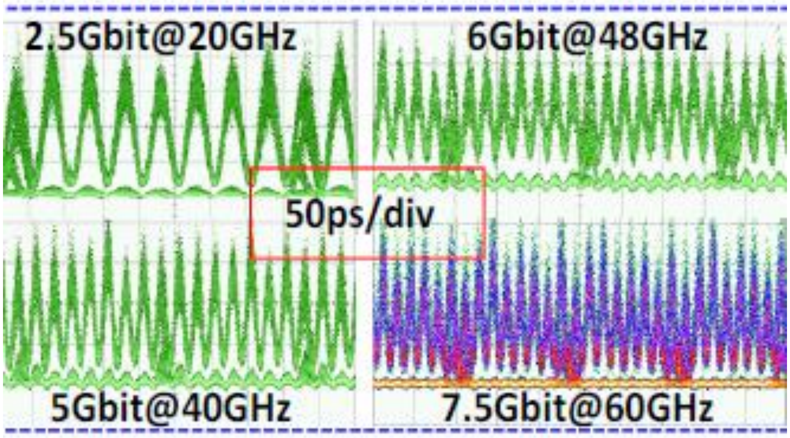


Fig. 3.7: Eye Diagrams of each converted Signal (taken from [16])

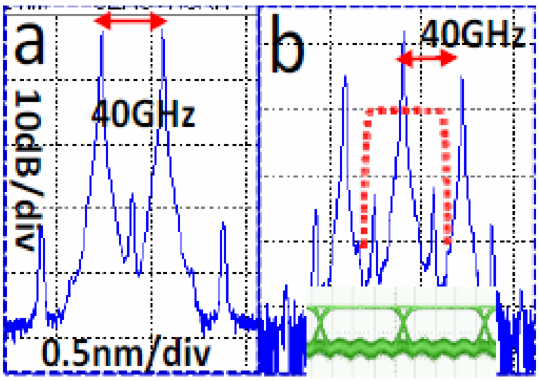


Fig. 3.8: Spectra of Upcoming RoF Signal: (a) before and (b) after Down-Conversion (taken from [16])

Based on the proposed method, a WDM signal up/down conversion was additionally demonstrated by coupling all four channels of the baseband signal at wavelengths of 1546.68, 1543.17, 1547.23 and 1548.63 nm with a bit-rate of 2.5 Gbit/s into the PALM and up converted to 20 GHz, as shown in the spectra of Figure 3.9 a. Each channel is then demultiplexed and demodulated by the setup Figure 3.5 f. Figure 3.9 a shows the eye-diagrams and measured BER curves are illustrated in Figure 3.9 b. The power penalty of 20-km SMF transmission is about 0.4 dB on average. To simulate the WDM ROF signal, four channel 2.5 Gbit/s data at 40 GHz sub-carrier are generated. The central wavelength of each channel is located at 1543.8, 1546.7, 1549.6 and 1552.5 nm, respectively. After down conversion and demultiplexing, clear "eyes" are acquired as shown in Figure 3.10. Measured BER curves show a 0.8 dB power penalty on average after 20 km SMF transmission.

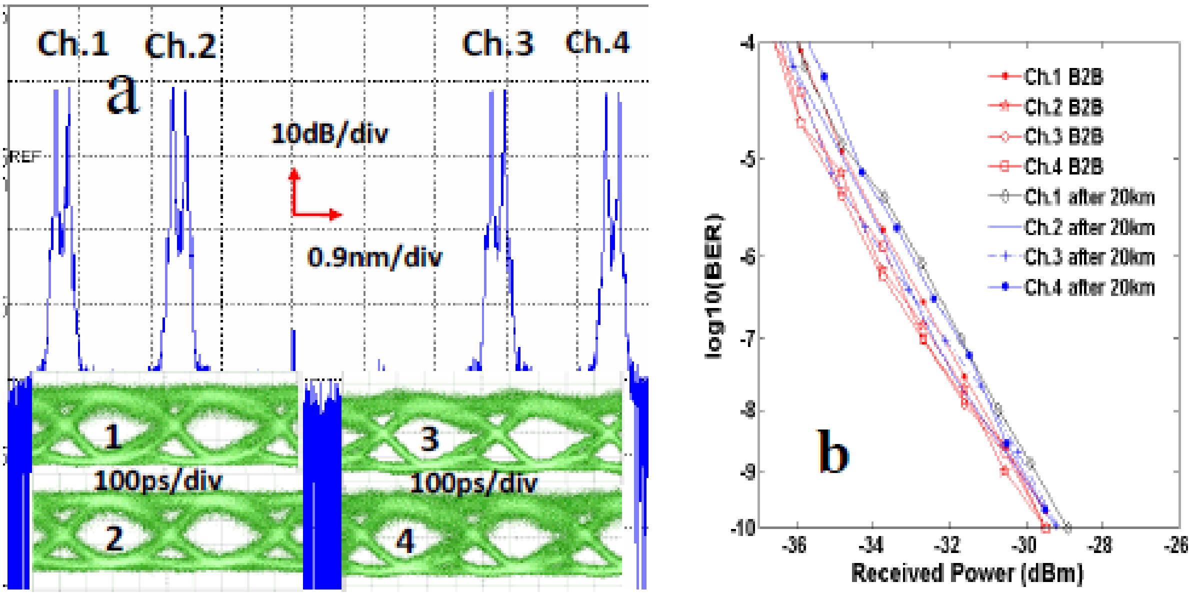


Fig. 3.9: WDM Up-Conversion Results. Four Channels are Up-converted to 20 GHz. (a) Optical Spectrum and demodulated Eye-Diagrams, (b) BER Curves (taken from [16])

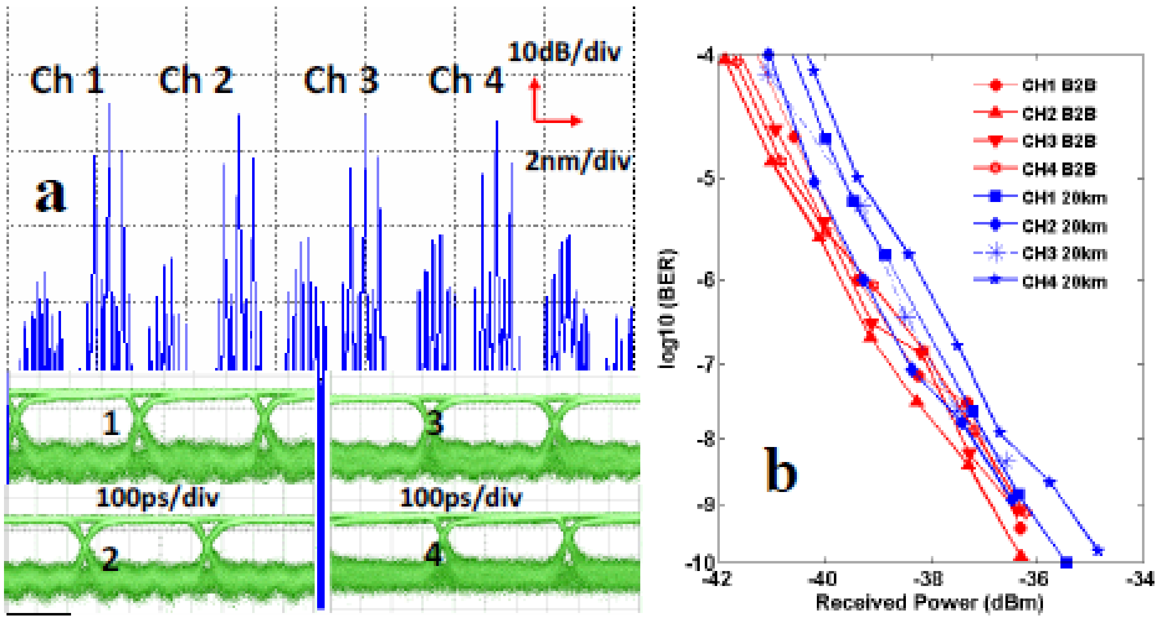


Fig. 3.10: WDM Down-Conversion Results. Four Channels are Down-converted from 40 GHz to Baseband. (a) Optical Spectrum and demodulated Eye-Diagrams, (b) BER Curves. (taken from [16])

A wide range of operating wavelength is practically required. For the first order FWM waves the free spectrum range is about 2.9 nm, which is mainly determined by the total dispersion of the single mode fiber (1 km SMF) and the converter frequency (40 GHz). Figure 3.11 shows the output power of the first order FWM idlers and the second order FWM waves from port 2 of PALM as a function of the input signal's wavelength (Colour line). Dots and curves indicate the measured and simulated values, respectively. As we can see in Figure 3.11, the optimal wavelength where the first order FWM waves are maximized, the second order FWM waves are minimized, which could be useful to achieve a higher harmonic suppression ratio (HSR) for the up converted signal.

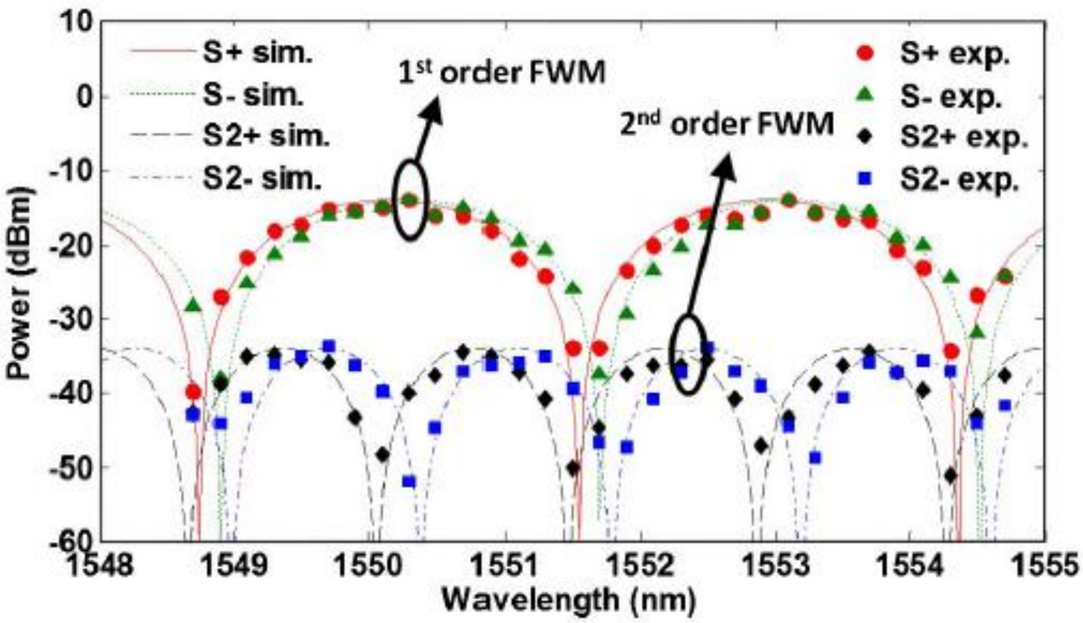
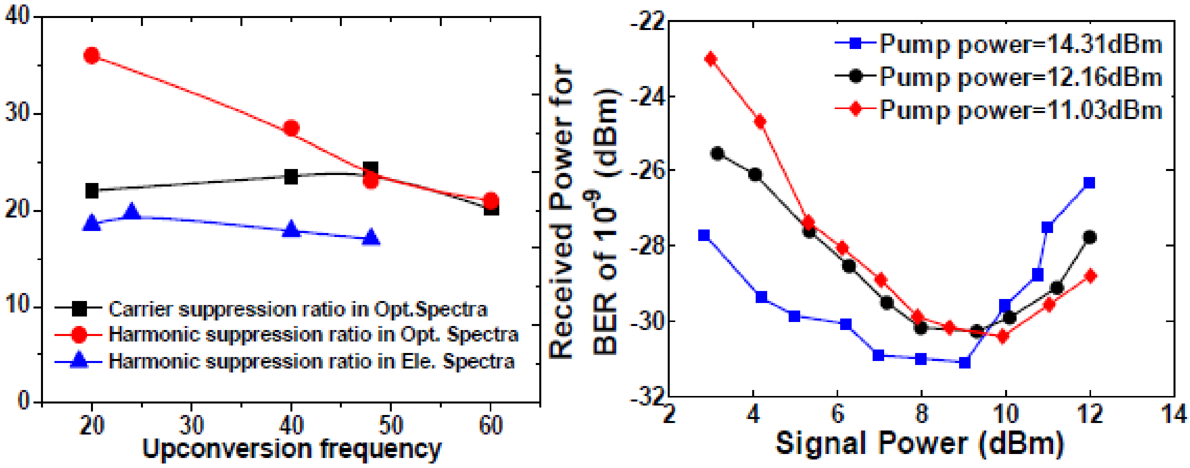


Fig. 3.11: Output Power of First Order FWM Idlers and Second Order FWM Waves (taken from [16])

The linearity of the converter is also an important parameter for the analog applications. By varying the converting frequency from 20 GHz to 60 GHz, the carrier and the harmonic suppression ratio of the up converter in both optical and electrical domains are measured, as shown in Figure 3.12-I. In the optical domain, CS ratio is relatively flat and above 20 dB, while the HSR decreases with the increase of the frequency due to the second order FWM. The HSR in the electrical spectrum is measured up to 50 GHz and keeps above 17 dB. Figure 3.12-II shows the power dependence of the up converter based on the minimum received power to achieve a BER of 10^{-9}. The optimal signal power for the converter with the pump power of 11.03 dBm is around 10 dBm and the optimal point decreases with increasing pump power from 11.03 to 14.31dBm [16].



(I) **(II)**

Fig. 3.12: (I) CSR and HSR of Up-Converter in Optical and Electrical Domain and (II) Power Dependence of BER Performance of Up-Converter (taken from [16])

3.3 Generation of RF Frequencies with Optical Sideband Filtering using a Single Laser Source

This technology is advantageously suited for high frequency and wide bandwidth applications with its "universal" frequency converter capabilities and is based on optical sideband filtering using a single laser source providing low phase noise generation of RF frequencies [17]. The block diagram of this photonic frequency architecture is shown in Figure 3.13.

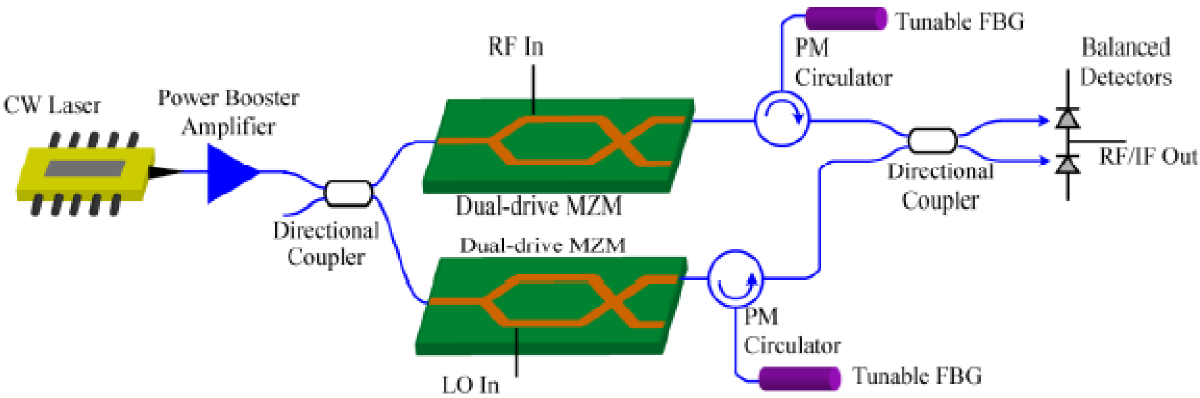


Fig. 3.13: Block Diagram of Photonic Frequency Converter (taken from [17])

A continuous wave (CW) laser source emits light that is amplified and split into two paths by a directional coupler. On the upper path, the light is modulated by the radio frequency (RF) or mm-wave signal using an electro-optic intensity modulator, which is a Mach-Zehnder intensity modulator (MZM), biased at the null point for maximum sideband power. The MZM creates RF sidebands on an optical carrier by modulating the phase of the optical carrier with the input RF voltage using the electro-optic properties of the modulator material. Then it converts the phase shift to an intensity modulation by combining the phase-modulated path interferometrically with an unmodulated path. One of the modulated sidebands is filtered using an optical bandpass filter. This is realized by combining a fiber Bragg grating and circulator. A fiber Bragg grating (FBG) is a section of optical fiber in which a periodic change in refractive index has been created. This sets up a diffraction grating through which a narrow range of wavelengths are reflected. The optical circulator passes the reflected portion of the spectrum back into the link.

On the lower path, the light is modulated by the local oscillator signal desired for frequency conversion, again using an MZM as a electro-optic modulator. With the use of a fiber Bragg grating and circulator, one of the local oscillator (LO) sidebands is filtered. The sidebands from the upper and lower paths are combined in a 2x2 optical coupler and sent to a pair of balanced photo detectors. Thus the LO sideband becomes the phase reference for the signal sideband, and the frequency spacing of these two sidebands determines the frequency of the signal at the detector output. The balanced photo detectors detect the upper and lower signals coming out of the 2x2 optical coupler and subtract them. Since the signals are out of phase by 180°, the subtraction at the detector results in the addition of the two signals, while any common-mode noise terms are subtracted.

The phase modulators is another modulator that can be used as electro-optic modulator. It can select higher order sidebands from the lower path in order to achieve higher frequency up- or down-conversion using a lower-frequency RF source as the LO input. For example an LO input of 10 GHz into a phase modulator produces sidebands at 10, 20, 30, … GHz, and the 30 GHz upper sideband can be combined with a signal's lower sideband at 5 GHz to produce an up-converted signal at 35 GHz. Or the 30 GHz upper sideband can be combined with a signal's upper sideband at 32 GHz to produce a 2 GHz IF signal.

The RF power of the LO signal and the efficiency of the two fiber Bragg grating filters, which form the optical power input level, primarily drive the performance of the converter. Due to the balanced detection, the noise terms can be divided into common mode noise terms and non-cancelling noise terms. Common noise terms are cancelled by the detector and include laser relative noise (RIN) from the signal and the LO path, amplified spontaneous emission (ASE)-beat noise, signal-ASE beat noise and LO-ASE beat noise. Shot noise from the signal, the LO and the ASE as well as thermal noise from matching impedance at the modulator and the detector and beat noise from the signal RIN and the LO RIN are part of the non-cancelling noise terms. The optical performance is achieved when the system is shot noise-limited, because of the linear gain of the shot noise with the photocurrent, while gain and output third-order intercept point (OIP3) increase with the square of the photocurrent [17].

3.4 RF Up- and Down-Converting Optoelectronic Oscillator for Spurious Suppression

For the application of local signals for radar systems and reference signals for clock recovery, oscillators are needed. Those generated signals from the oscillator require a low phase noise characteristic. One of the most promising approaches, is the use of an optoelectronic oscillator (OEO), because of its high-Q element with a long optical fiber in the oscillation loop. On the other hand, a lot of narrowly-spaced oscillation modes induce strong spurs at the multiple frequency around the oscillation frequency in a long oscillation loop. A extremely narrow band-pass filter (BPF) is necessary to make the oscillator operate at a single mode. The realization of this BDF is more difficult, therefore a multi-loop OEO has been proposed. Since this OEO consists of more than two loops whose lengths are set to be different, the different spaced spurs from each loop are averaged and suppressed. However, the instability of this OEO deriving from temperature fluctuation and vibrations tend to get higher relative to a single-loop OEO [18].

To overcome these problems a RF up/down-converting OEO using a BPF for spurious suppression has been proposes. Figure 3.14 a shows the configuration of a conventional OEO, which consists of a laser diode (LD), an electro-optic modulator (EOM), an optical fiber, a photo diode (PD), a BPF, a low-noise RF amplifier (LAN) and a splitter, where f_{OEO} is the frequency of the output signal from the PD and the output signal frequency of the OEO and f_{BPF} is the central frequency of the BPF. The EOM modulates the intensity from the laser that is sent from the LD. The modulated laser from the EOM is sent to the PD through the optical fiber, and converted to RF signal, which is then launched to the BPF and the spurs including this signal are suppressed. This suppressed signal is amplified by the LNA and split into two parts by the splitter. The one of two parts is used for the output signal of this OEO, and another is sent to the EOM for modulation signal. Since the output laser from the EOM is converted, the RF signal and this signal goes back to the EOM for modulation, a negative feedback loop is formed in this OEO. As a result, this OEO oscillates at the central frequency of the BPF.

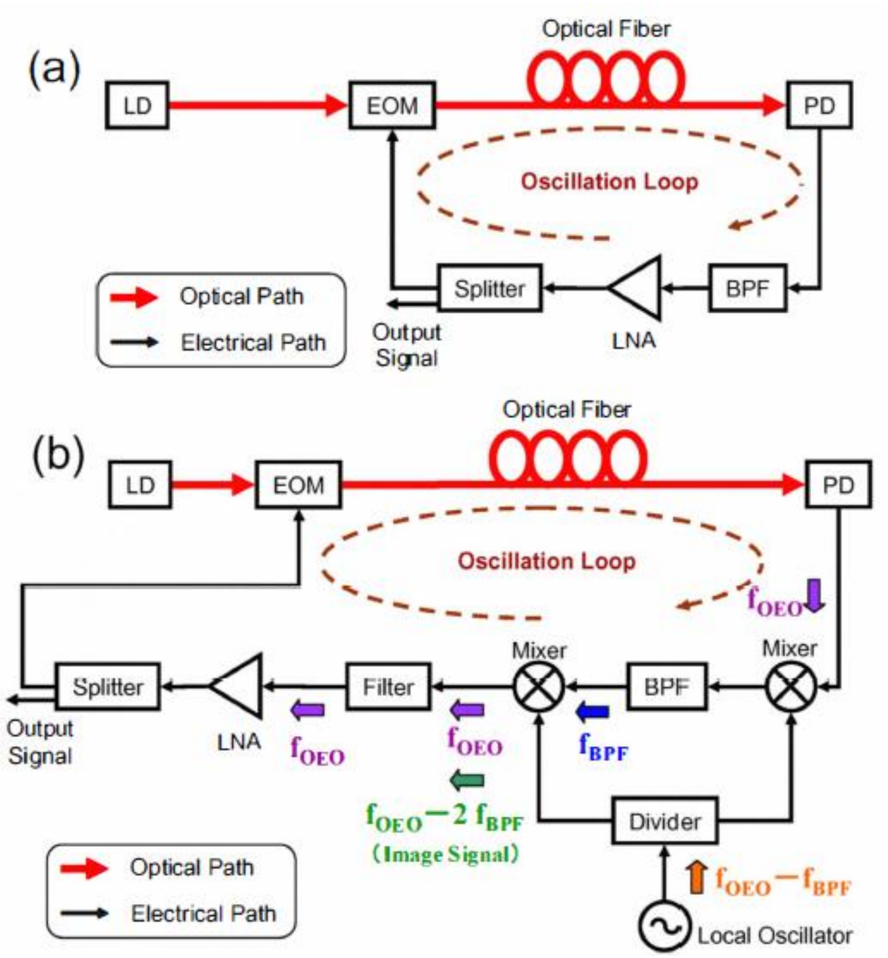


Fig. 3.14: Configuration of the OEO: (a) Conventional OEO (not using RF mixers) and (b) Proposed OEO (using RF mixers) (taken from [18])

The proposed OEO, shown in Figure 3.14 b, arranges RF mixers in front and behind the BPF. An other oscillator, as a local oscillator, is used for generating local signals to input into the former two mixers. To divide the local signal from the local oscillator, a divider is used. The frequency of this local oscillator is set to the difference between the output signal frequency of this OEO and the central frequency of the BPF. For that reason, the output signal from the PD is down-converted to the central frequency of the BPF by the mixer in front of the BPF. After this RF signal passes through the BPF, this signal is up-converted to the frequency before being down-converted by the mixer behind the BPF. Therefore, it is able to suppress the spurs as long as the bandwidth of the BPF is sufficient to cut off the spurs, regardless of the central frequency of the BPF. The fractional bandwidth of the BPF is wider than that of the BPF in the conventional OEO. Additionally, the image signal generated from the mixer behind the BPF is suppressed by a filter setting behind the mixer.

To demonstrate the spurious suppression effect, the system of the conventional OEO and the proposed OEO was set up. The oscillation frequency f_k and the frequency of the BPF f_{BPF} in the conventional OEO are set to 10 GHz. f_{BPF} in the proposed OEO is set to 30 MHz, thus the oscillation frequency of the local oscillator is set to 9.97 GHz. The central frequency of the

BPF including the conventional OEO is 10 GHz and the bandwidth of that is 4.8 MHz. The theoretical value of the maximum spurious level in the conventional OEO and the proposed OEO, as well as the measurement of the phase noise are illustrated in Figure 3.15.

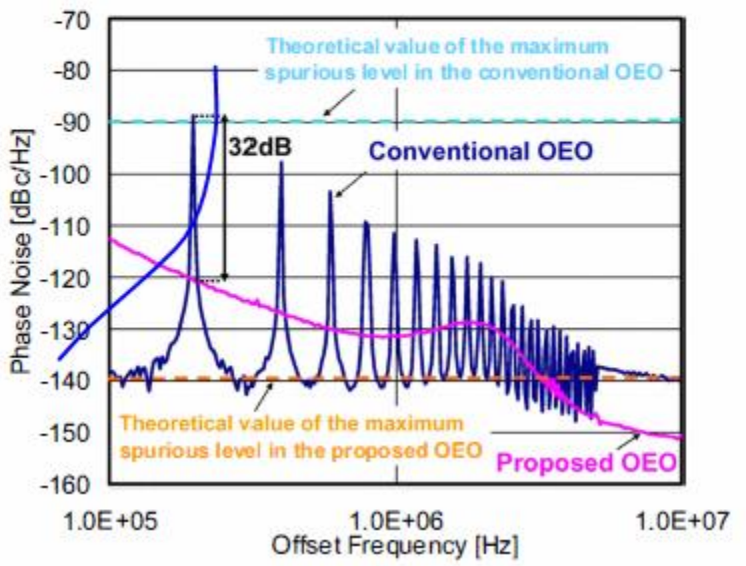


Fig. 3.15: Measurement Result of the Phase Noise in the Conventional OEO and the Proposed OEO (taken from [18])

The measurement value of the maximum spurious level in the conventional OEO is -89 dBc, whereas that in the proposes OEO is less than -121 dBc. Thus, the proposed OEO demonstrates more than 32 dB spurious suppression compared with the conventional OEO. Furthermore, the measurement value of the maximum spurious level is nearly consistent with the theoretical value in the conventional OEO. On the other hand, in the proposed OEO, the measurement value is highly different from the theoretical value. One reason might be the degradation of the phase noise of the proposed OEO due to superposition of the phase noise of the local oscillator is too severe to distinguish from the spurs [18].

3.5 OFDM mm-Wave Signal Generation

A flexible scheme which can simultaneously realize photonic frequency up conversion for intermediate frequency (IF) band signals and mm-wave signal generation has been developed recently. To generate the mm-wave carrier and up convert the IF band signal to the mm-wave carrier, the inherent nonlinearity of dual driver Mach-Zehnder modulator (DDMZM) and copolarized-pumped four-wave mixing (FWM) in an optical semiconductor amplifier (SOA) are utilized. The mm-wave generation process and the frequency up conversion process are both completed by the FWM effect in the SOA, and no extra Mach-Zehnder modulator (MZM) is needed to modulate the IF band signal to the mm-wave carrier. Besides, in this proposal, the products generated on the both side of the probe light to obtain photonics mm-wave are used. As a result, this scheme can be used in a multi-wavelength photonics mm-wave generation system using only one pump light and multi-wavelength probe light [19].

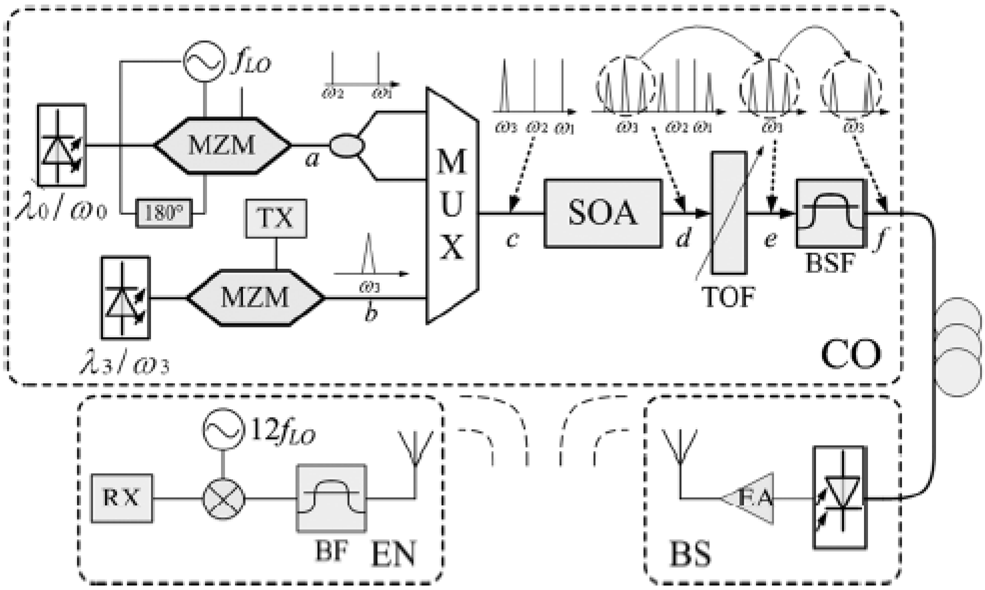


Fig. 3.16: Schematic Diagram of OFDM mm-Wave Generation with DDMZ and SOA using Twelvefold OFDM Strategy (taken from [19])

The central office (CO), base station (BS) and the end notes (EN) built up the main blocks for the schematic diagram of an mm-wave band OFDM signal generation, as shown in Figure 3.16. In the CO, the generates CW light of LD_{λ_3/ω_3} is used as the probe signal carrier with the frequency of $\omega_3(\lambda_3)$. A modulated OFDM signal is generated from the OFDM TX and then converted to the optical domain by a single arm MZM. The mm-wave carrier generation is attributed to the nonlinear modulation of the dual driver MZM (DDMZM). The CW of LD_{λ_0/ω_0} is injected into the DDMZM to generate the copolarized pump light-wave. The two RF bias electrodes of the DDMZM are driven by two reversed-phase sinusoidal waves from the local oscillator LO. As various harmonics can be achieved through adjusting the modulation index of the DDMZM, a very high modulation index is used in this scheme, to maximize the third order harmonics to get an optical carrier suppressed (OCS) like signal with a frequency detuning (FD) six times greater than the local oscillator (LO).

The WDM multiplexer (MUX), which is a comb filter composed of a group of bandpass filters, is used to suppress undesired harmonics. It extracts and separates the up- and lower-sideband (ω_1 and ω_2 in Figure 3.16) of the third order harmonics as well as the co-polarized-pump light of the FWM.

After being multiplexed, the three wavelengths (ω_1, ω_2 and ω_3) participate in the FWM inside the SOA. Due to the third-order electric susceptibility and beating process in the phase-matching state, refractive index grating at $\Delta\omega = \omega_1 - \omega_2$ is generated in SOA. Both, degenerate FWM (D-FWM) and nondegenerate FWM (ND-FWM) occur and new sidebands are generated. For this propose, only the first order sidebands around the proble light are required to generate the mm-wave signal. For fiber dispersion suppression and in order to re-double the mm-wave carrier frequency, a tunable filter (TOF) and a bandstop filter (BS) are used to filter out the two sidebands to obtain a OCS-like signal. Furthermore a FD with the frequency twelve times of that of the LO can be achieved between the upper sideband (USB) and the lower sidebands (LSB).

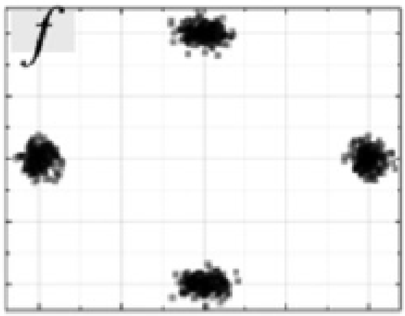


Fig. 3.17: Received Constellation (taken from [19])

The optical OFDM mm-wave signal is detected at the BS after going through 40 kilometres of single mode fiber by a photodiode. After the photo detection, the mm-wave band OFDM signal can be generated The received constellation of the QPSK modulated OFDM signal is indicated in Figure 3.17. The transmission distance of the mm-wave OFDM signal is manly limited by laser phase noise, phase distortion and amplifier noise induced by the fiber dispersion and fiber loss. After amplification, the OFDM signal is released from the antenna to the air link at BS. At the EN of each subcarrier, the mm-wave OFDM signal is received and down converted to the original IF band by mixing with a LO at a frequency twelve times that of the LO in the CO [19].

3.6 Down-Conversion Detection using a Glow Discharge Detector

Theoretical and experimental investigations of the interaction between microwave frequency and glow discharge tubes have shown, that the use of a Glow Discharge Detectors (GDD), a miniature neon indicator lamps, as a electromagnetic radiation detector is advantageous due to their low cost, wide dynamic range, electronic ruggedness, broad spectral range, room temperature operation, fast response time and simplicity of use. Furthermore the results on the investigation of GDD performance in the millimetre wavelength and THz radiation spectra regions are similar to the performance of pyro-electric detectors, with good Noise Equivalent Power (NEP) for a room temperature detector. Down conversion based on heterodyne detection using a GDD at 10 GHz showed 40 times better sensitivity compared to direct detection and at 300 GHz the sensitivity was at least on order to magnitude superior. This can be improved by increasing reference beam power [20].

The well known Heterodyne detection in electronics and optics, is a method of detecting radiation by non-linear mixing with radiation of a reference frequency. Because of the linearity of the GDD detection mechanism, the GDD is not capable to act as a direct mixer and thus a heterodyne detector. To carry out heterodyne detection with a GDD, two synchronized THz sources based on RF multipliers have been used. The modulation of the first source can demonstrate direct detection. By synchronizing the second source to the first source it can be shifted relatively to the first source. The connection of the two sources yield two synchronized THz sources, the first is a 300 GHz source and the second is a 300 GHz +

Δf source, where Δf stands for the frequency difference between the two sources, which were coupled out of free space by horn antennas.

With the use of a dielectric Beam Splitter (BS) configuration the two THz beams were combined and focused between the two electrodes of the GDD with an Off Axis Parabolic Mirror (OPM), as shown in Figure 3.18. A band pass of 20 KHz and a low noise voltage pre-amplifier, connected to the GDD, built the electronic detection circuit. With the use of an oscillator the output signal of the pre-amplifier was recorded.

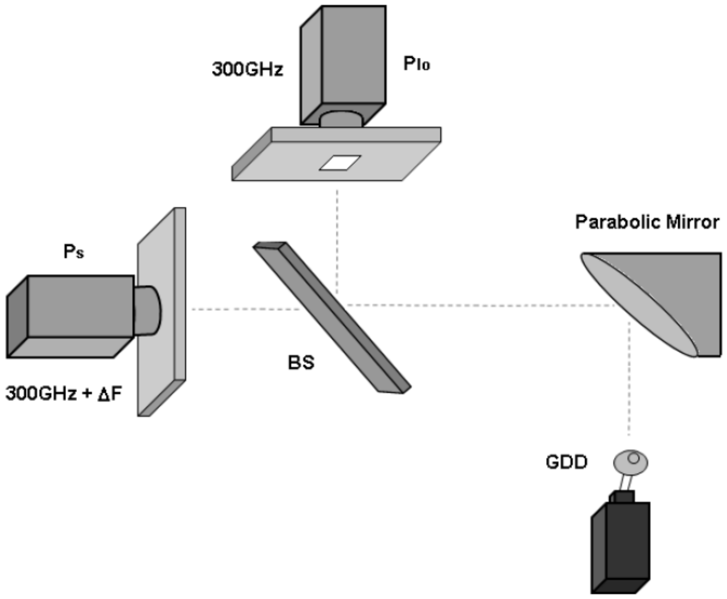


Fig. 3.18: Experimental Setup for Heterodyne Detection with Two Synchronized THz Sources differing in Frequency by Δf. (taken from [20])

The direct detection using one modulated signal was performed by directing the THz modulated signal to the GDD. Figure 3.19 a shows the GDD signal after amplification of 100 and band pass filter of 20 kHz.

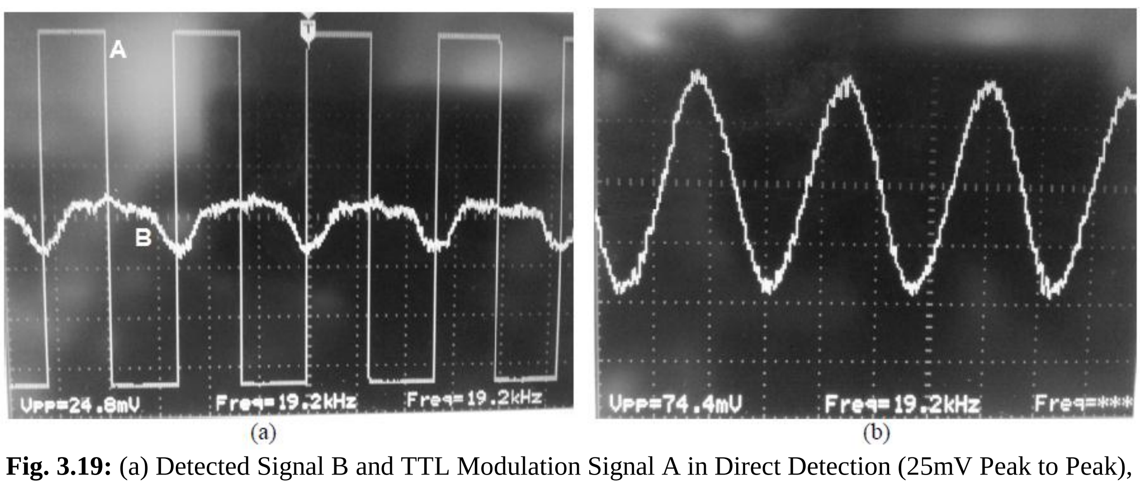


Fig. 3.19: (a) Detected Signal B and TTL Modulation Signal A in Direct Detection (25mV Peak to Peak), (b) Detected Signal in Heterodyne Detection (75mV Peak to Peak) (taken from [20])

With the use of two synchronized sources P_{lo} (power level of the local oscillator, 56 μW) and P_s (power level of the signal, 76.4 μW) the heterodyne detection was demonstrated. The transmission/reflection ratio of the beam splitter was about 70/30. Figure 3.19 b shows the heterodyne detection. The detected signal using heterodyne detection is higher by the factor 3 and less noisier than the detected signal using direct detection.

By repeating the comparison with different power levels of P_s, its influence on the detected signal was investigated. In Figure 3.20 the summarized results of the detected signal as a function of P_s on the detector active are plotted. For heterodyne detection the LO was of constant power P_{lo} =56 µW on the active area of the GDD

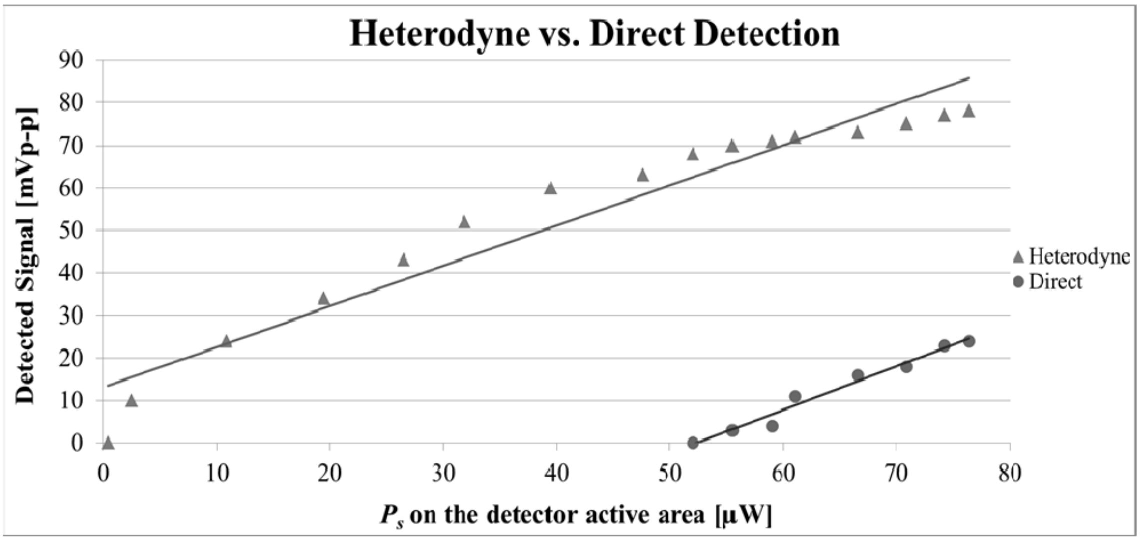


Fig. 3.20: Heterodyne and Direct Detection Summary Result Graph (taken from [20])

For low values of signal powers below 55,5 µW direct detection could no longer be used, while heterodyne detection still detects well. The lowest detected signal with the use of direct detection was about 3 mV peak to peak, with a signal power of 55.5 µW on the detector active area, whereas the lowest detected signal with heterodyne detection was about 10 mV peak to peak, with signal power 2.54 µW. The Noise Equivalent Power (NEP) was NEP=392$\left[nW/\sqrt{Hz}\right]$ for direct detection and NEP=127$\left[pW/\sqrt{Hz}\right]$ for the heterodyne detection. The NEP of the heterodyne detection significantly improves as P_{lo} increases [20].

3.7 Discussion of the new Radio Frequency Conversion Technologies

For frequency conversion methods it is desirable to use optical methods in order to potentially reduce the required bandwidth of the electronic drive circuitry as well as to enable considerably higher frequencies. Several approaches for the optical-based up/down-conversion necessitate an optical filter at the converter output to remove one or more optical carrier wavelengths and to achieve higher fold frequency. The proposed method of WDM RF signal up/down conversion using an optical parametric loop mirror based on the non-degenerate FWM overcomes this limitation. It does not require a narrow band optical filter, which may potentially improve the dynamic range and tunability of a conversion system [16].

The capabilities of the new ‘universal’ photonic converter based on optical sideband filtering using a single laser source is advantageously suited for high frequency and wide bandwidth applications and enables a new dimension of on-orbit frequency reconfigurability. The previously limitation of a reconfigurable mission payload inside the frequency range of the RF front end electronics of the payload has been abolished with this new photonic converter. Regarding software defined payloads, this paradigm shift can now adapt as never before to new and changing mission objectives to include not only additional waveforms, data protocols, and signal processing algorithms, but also extreme variations in frequency bands of operation including mm-Wave and above [17].

The newly proposed RF up- and down-converting optoelectronic oscillator is allowed to use BPF whose fractional bandwidth is more than 330 times wider than that of the BPF in the conventional OEO. This leads to the allowance of using a long optical fiber due to its achievement of lower phase noise without spurs. In terms of degradation of the phase noise of the proposed OEO, a future optimization should be taken into consideration [18].

The simultaneous realization of photonic frequency up conversion for intermediate frequency (IF) band signals and mm-Wave OFDM signal generation uses signals with a frequency of 12 times than that of LO to generate tens of GHz mm-Wave carriers for the OFDM signals. The distribution is realized with dual driver Mach-Zehnder modulator and semiconductor amplifier [19].

With the use of a Glow Discharge Detector for heterodyne down-conversion detection the detection sensitivity improved. The detection of signals lower by a factor of about 20 than with direct detection can be achieved. The GDD is considered for heterodyne THz imaging systems, because imaging at 300 Ghz source will show better resolution of the object with smaller radiation wavelength. However, higher local oscillator power would be desirable [20].

3.8 Seamless Integration of 100-G Wire Line and 100-GHz Wireless Link System

The fiber-wireless link in the W-band (75-110 GHz) based on optically-modulated signal generation technique has recently been intensively studied, for the reason that it is expected to provide multi-gigabit mobile transmission. This can be of great use for the smart phones (Nokia and Samsung), that have recently been equipped with 8k and 4k Super High Definition (SHD) cameras that require transmission speed for uncompressed SHD video images of 60 Gbit/s and 30 Gbit/s [21].

Recently a seamless integrated fiber-wireless system that delivers 108 Gbit/s signal through 80 km fiber and 1 m wireless transport over free-space at 100 GHz, adopting polarization-division multiplexing quadrature-phase-shift-keying (PDM-QPSK) modulation and heterodyning coherent detection has been experimentally demonstrated. It is the first time that a 100 Gbit/s signal has been delivered through fiber wire line to the base station, followed by wireless transmission at 100 GHz through free space.

Figure 3.21 shows the setup of the experiment. The main difference between the radio-over-fiber technique and this new proposed fiber-wireless system is, that the local oscillator is located at the up-converter instead of the optical baseband transmitter and as a result the optical carrier isn't transmitted with the optical baseband signal over the fiber.

At the optical baseband transmitter, there is an external cavity laser (ECL). The continuous-wavelength (CW) light-wave from ECL is modulated by in-phase/quadrature (I/Q) modulator, which is driven by a 27 Gbaud electrical binary signal, that is generated from an pulse pattern generator (PPG). For optical QPSK modulation, the two parallel Mach-Zehnder modulators (MZMs) in I/Q modulator are both biased at the null point and driven at the full swing to achieve zero-chirp 0- and π-phase modulation. The phase difference between the upper and lower branches of I/Q modulator is controlled at π/2. The polarization multiplexer is realized by comprising a polarization-maintaining optical coupler (OC) to halve the signal into two branches, an optical delay line (DL) to provide a 150 symbol delay, an optical attenuator to balance the power of two branches and a polarization beam combiner (PBC) to recombine the signal. The generated signal is launched into 80 km single-mode fiber, without optical dispersion compensation. An Erbium-doped fiber amplifier (EDFA) is used to compensate the fiber loss.

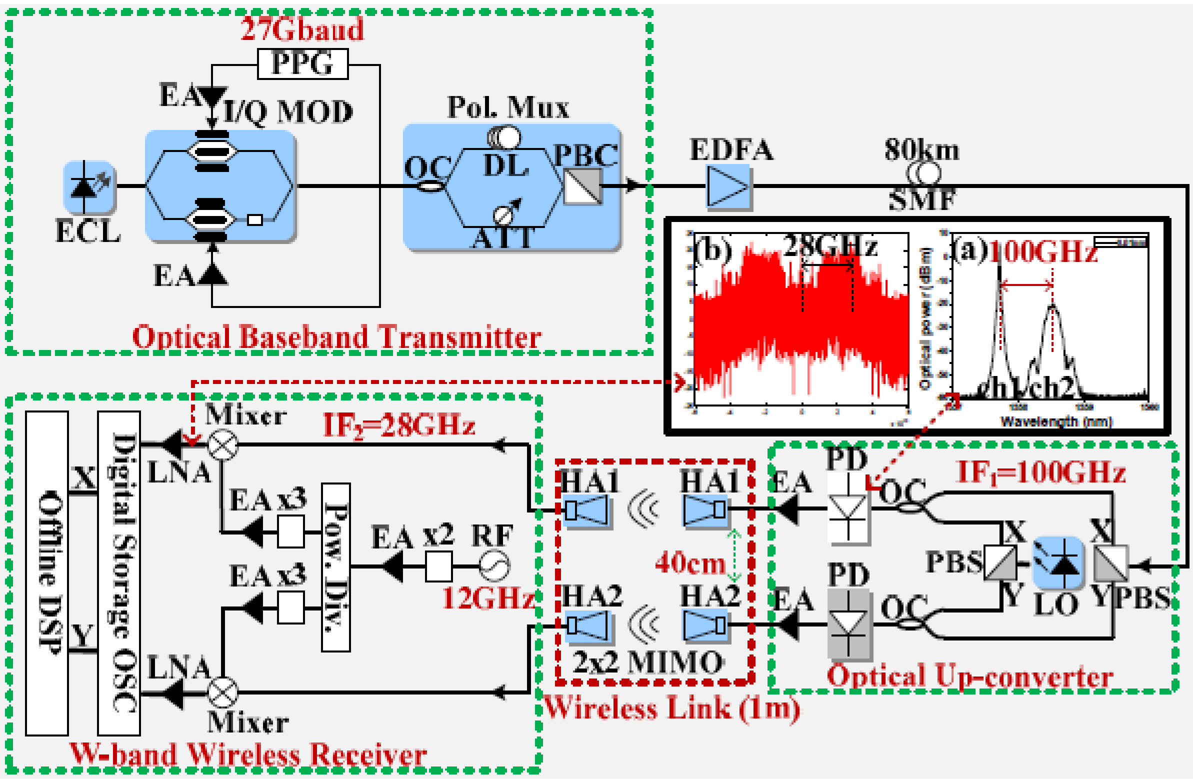


Fig. 3.21: Experimental Setup: (a) X-Polarization Optical Spectrum (0.01 nm Resolution) after Polarization-Diversity Splitting, (b) Electrical Spectrum after First-Stage Down Conversion (taken from [20])

The optical up-conversion is realized by optical polarization-diversity heterodyne beating. Another ECL is used as local oscillator (LO) , which has 100 GHz frequency offset (IF1=100 GHz) relative to the received optical signal. Two polarization beam splitters (PBSs) and two OCs are used to implement polarization diversity of the received optical signal together with LO in optical domain before heterodyne beating. X- or Y-polarization component of the PDM-QPSK signals after the PBS does not mean that only X- or Y-polarization signal exists at each output port from the PBS. In fact, each output port contains both X- and Y-polarization signals. For simplification one output port of the PBS is defined as X-polarization component and the other as Y-polarization. Two 100 GHz photo detectors (PDs), each with 3 dB bandwidth of 75 GHz, are used to directly up-convert the X- and Y-polarization components of the optical PDM-QPSK into W-band wireless signal by beating with LO. Then two parts of 100 GHz wireless signal carried on X- and Y-polarization components independently pass through two 100 GHz narrowband electrical amplifiers (EAs) with 32 dB gain, and then, are simultaneously sent into a 2x2 multiple-input multiple output (MIMO) wireless air link Each pair of horn antennas (HAs) has a 0.5~1.5 m wireless distance, the X- and Y-polarization wireless links are parallel and two pair of transmitter (receiver) HAs have a 40 cm distance. Each HA has a 25 dBi gain. Inset (a) shows the X-polarization optical spectrum after polarization-diversity splitting. Here, ch1 denotes the LO, while ch2 the received signal. The frequency spacing and power difference between ch1 and ch2 is 100 GHz and 20 dB, respectively.

At the W-band wireless receiver, two-stage down conversion is implemented for the X- and Y polarization received components which is firstly done in analog domain based on balanced mixer and sinusoidal radio frequency signal, and then in the digital domain based on digital processing (DSP). A 12 GHz sinusoidal RF signal firstly passes through an active frequency doubler (x2) and an EA in serial, and is then halved into two branches by a power divider. Next, each branch passes through a passive frequency tripler (x3) and an EA. As a result of this cascaded frequency doubling, an equivalent 72 GHz RF signal is provided for the corresponding balanced mixer. Therefore, the X- and Y-polarization components centred on 28 GHz (IF2 = 28 GHz) are obtained after first-stage down conversion, as shown in inset (b). Each band-pass low-noise amplifier (LNA) after the mixer is centred on 100 GHz and has a 5 dB noise figure. The analog-to-digital conversion is realized in the real-time oscilloscope with 120 GSa/s sampling rate and 45 GHz electrical bandwidth. The second down conversion then takes place with the DSP which includes down conversion, chromatic dispersion compensation, I/Q Separation, equalization based on constant modulus algorithm (CMA), carrier recover, differential decoding and bit-error ratio (BER) counting. Figure 3.22 a shows the detailed DSP and Figure 3.22 b the received constellation.

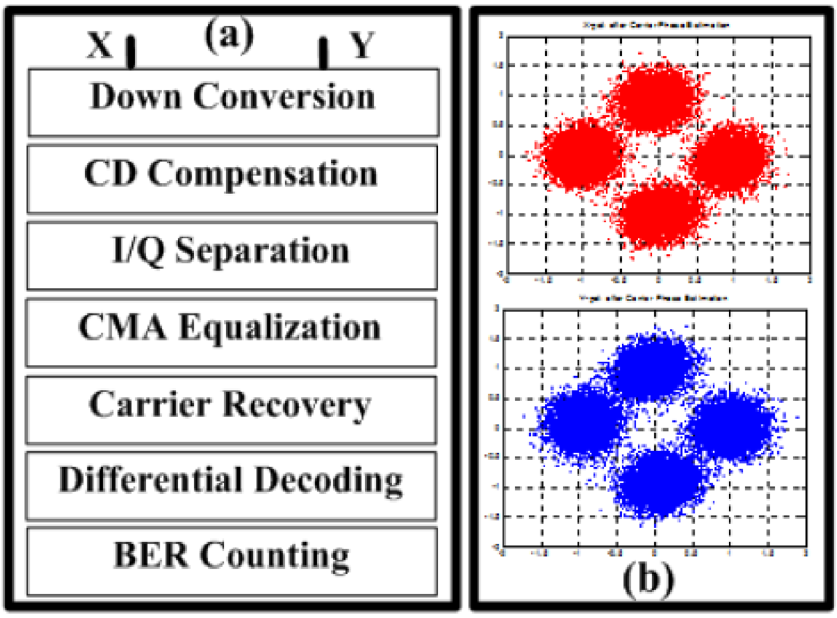


Fig. 3.22: (a) Detailed DSP, and (b) Received Constellation (taken from [20])

To realize polarization de-multiplexing and remove the crosstalk between two pairs of transmitter and receiver MIMO HAs, the digital FIR filters based on CMA algorithm are employed in DSP. The bit-error ratio (BER) for the 108 Gbit/s PDM-QPSK signal was measured to be less than the pre-forward-error-correction (pre-FEC) threshold of 3.8×10^{-3} after both 1-m wireless delivery at 100 GHz and 80 km SMF transmission [21].

This new method of ultra high-bit rate (> 100 Gbit/s) wireless communication using W-band frequencies can be of great interest for future technologies.

3.9 Wired and Wireless Integrated Wide-Area Access Network with Photonic Up- and Down-Conversion

One of the most attractive candidates for future optical access is the wavelength-division-multiplexing passive-optical-network (WDM-PON) as it can easily upgrade the bandwidth for each user and provide various services per wavelength. Recent proposals establish to offer wireless and/or wired services over WDM-PON [22].

To accommodate various types of broadband wireless services in smaller radio cells with many base stations (BS) over WDM-PON, a flexible and cost-effectively method is the radio over fiber (RoF) technique, as it can easily transmit RF signals over a wavelength.

One of the technical issues of conventional RoF based on sub-carrier modulation (SCM) is the distortion of the RF signal due to fiber dispersion. A countermeasure to solve this technical issue is the photonic up- and down-conversion of the RF carrier frequency.

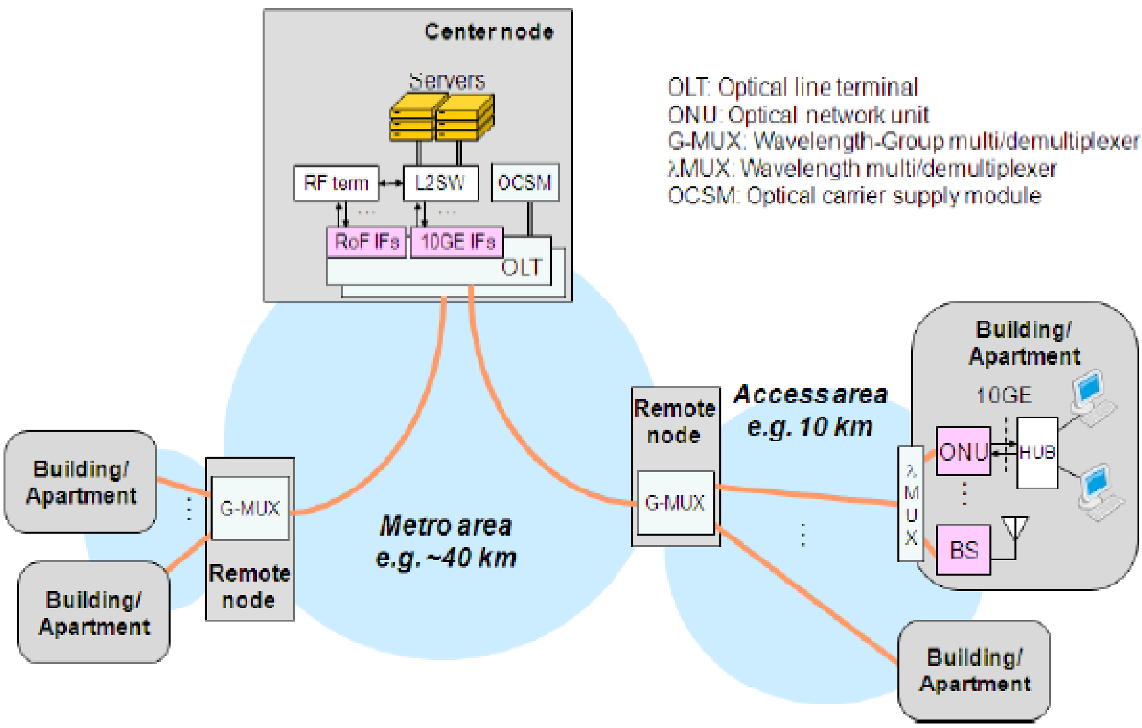


Fig. 3.23: Wired and Wireless Integrated Wide-Area Access Network (taken from [22])

Figure 3.23 shows the wired and wireless wide-area access network based on long-reach WDM-PON. The centre node includes an optical carrier supply mode (OCSM) and optical line terminals (OLT). The OCSM is built up by an optical frequency comb generator that generates the multi-wavelength carriers to several OLTs, which have interfaces for RoF access and high speed optical access (10 Gigabit Ethernet). The system structure is simplified with the RoF approach by launching broadband RF signals through optical fibers.

The photonic up- and down-conversion is an attractive RoF approach with the millimetre band. It converts two optical frequencies with heterodyning, whose difference correspond to the RF (e.g.60 Hz) and with the modulation of one of the two frequencies before the fiber transmission, the RF signal can be extracted by heterodyne detection after the transmission. This method reduces the fiber dispersion and eliminates the local RF generator in each base station. The OCSM is used to provide precise frequency control between any two wavelengths for the generation of a stable RF signal after the detection and is also used for multiplexing different RF signals.

The group multi/demultiplexer (G-MUX) in every remote node divides/combines the DWDM channels into/from several groups of wavelengths and are dedicated to a building/apartment, where a wavelength pair can deliver RoF access with a BS or optical access via an Optical Network Unit (ONU).

With this presented technique broadband optical digital transmission and millimetre RF signals transmission can be achieved simultaneously over long-reach WDM-PON [22].

4 Evolving Technologies and Technological Outlook

The only alternative to cope with the demand for constant volume increase of bandwidth means utilising the potential of fiber optics bandwidth of over 50 THz, thus, inseparable with the future of communication [23].

To optimally exploit this specific potential, need of further technological innovations is essential in main domains, which are for the following:

- Devices, components and subsystems
- Transmission technologies
- Node technologies
- Networking software

Evolution in those fields is last but not least also driven by the increase of bandwidth requirement. As a function of demand, optical technologies become more economical and feasible.

Lower cost of new technology application will further drive demand in the market. Beside technological innovations, development of components appear in miniaturisation, lower power consumption and elaboration as modules and in tendency to all optical devices.

In the sense of avoiding detour of use for electrical signals, currently a lot of research is undertaken in the field of integrated optics for communication systems and sensors to create, design and develop new modules as integrated optical circuits, accommodating all required functionalities for an optical communication network.

4.1 Key Issues

Synchronous optical network/Synchronous digital hierarchy (SONET/SDH) with large capacity DWDM as basis, represents the dominant system of today's networking architecture.

Any increase of internet traffic volume requires:

- Higher speed, capacity and reliability
- The support of various types of interfaces

Service providers had been challenged to meet the same system performance parameters when moving from 10 Gbit/s to 40 Gbit/s. Service providers deploying a Ciena 40G coherent solution can evolve their networks to add 100 Gbit/s wavelengths as soon as their business dictates, deploying 100 Gbit/s on their existing network with similar transmission attributes as those currently allowed today [23][24].

The challenge of generating and transmitting at even higher speeds require further advanced techniques.

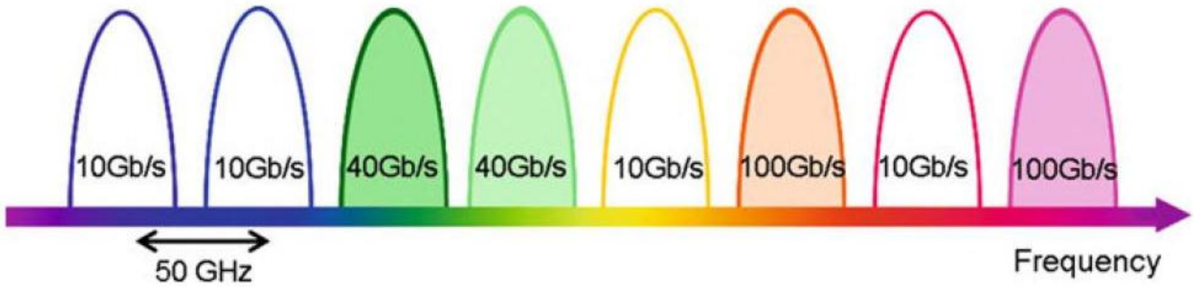


Fig. 4.1: Illustration of a Channel Plan (10, 40 and 100 Gbit/s Channels coexisting in a 50 GHz spaced DWDM System for In-Service Capacity Upgrade) (taken from [23])

4.2 Main Improvements

Since it was first deployed, commercial transmission capacity has increased more than one hundred thousand times. Optical transport costs have traditionally been lowered by increasing per-channel data rates and spectral efficiency (SE), with 100 Gbit/s wavelength-division multiplexed (WDM) technology being made commercially available in 2010.

Speed increase of Ethernet:

- 155 Mbit/s first optical transmission system was installed in the 1980s

- 10 Gbit/s transmission bandwidth speed by 2006
- 40 Gbit/s high-speed standards developed by the Institute of Electrical and Electronics Engineers by sending frames at 40 and 100 Gbit/s over multiple 10 Gbit/s or 25 Gbit/s lanes.
- 100 Gbit/s transmission becomes a commodity interface since 2012
- 200 Gbit/s experiments have been carried out to achieve these high bit rates
- 450 Gbit/s transmission research groups are focusing on standards and technologies
- 1 Tbit/s transmission are topics in conferences on optical communications proposing forward-looking solutions

The current laboratory fiber optic data rate record, held by Bell Labs in Villarceaux (France) is multiplexing 155 channels, each carrying 100 Gbit/s over a 7000 km fiber. Nippon Telegraph and Telephone Corporation has also managed 69.1 Tbit/s over a single 240 km fiber (multiplexing 432 channels, equating to 171 Gbit/s per channel). Bell Labs also broke a 100 Pbit/s km barrier (15.5 Tbit/s over a single 7000 km fiber) [25][26].

4.3 Potentials of Further Increase of Data Rate

Increased data rate per wavelength, advanced detection schemes such as differential detection, self coherent detection (SCD) and digital coherent detection (DCD) provide major breakthroughs [23][24].

Together with the advanced optical modulation formats increase, tolerance to optical noise and/or transmission impairments., such as chromatic dispersion (CD) and polarisation mode dispersion (PMD) and fiber non linearity appear, which are limiting factors for high speed transmission.

Advanced detection schemes enable high spectral efficiency (SE) optical modulation formats supporting higher data rate**.** Coherent communication systems have significantly progressed in past few years, mainly due to advances in digital signal processing techniques.

Enabling technologies for meeting the requirements of high capacity and high bit rate operation are based on spectrally efficient multiplexing and modulation formats, single-carrier polarization multiplexing QPSK (which is currently used in 100G commercial products), multi-carrier optical orthogonal frequency division multiplexing, multicore or multimode spatial multiplexing, and coherent detection based on digital signal processing.

For high-speed optical signal transmission, a traditional transponder with direct modulation and detection has a simple, low-cost architecture. However, the transmission distance at high bit rate is limited by the rigid requirements of high optical signal-to-noise ratio, polarization mode dispersion, and optical/electrical filtering effects.

Coherent detection based on digital signal processing is becoming the trend for optical signal receivers because it can lift these limitations. The change from direct detection to coherent detection is revolutionary. Receiver architecture, transmission fiber and distance, and network management will be completely reshaped from previous direct-detection systems.

At the moment there are proposals for:

- 200 Gbit/s direct-detection optical orthogonal frequency division multiplexing superchannel (DDO-OFDM-S) and optical multiband receiving method (OMBR).

- 450 Gbit/s wavelength-division multiplexed (WDM) channels over the standard 50 GHz ITU-T grid at a net spectral efficiency (SE) of 8.4 bit/s/Hz.

4.4 Synergetic Effects of Photonic and Electrics

The synergetic effect between electrical and photonic switching, on the basis of interaction between optical signals and electrical signals in the frequency range of laser light and nanometer-wave, lead to a rapid development over the last decades resulted in wideband technologies and sophisticated devices.

Global consumption of fiber optic components in communication networks grew from 2.5 million $ in 1975 to 15.8 billion $ in 2000. Projections are for 740 billion $ in 2025. As to forecast accelerating price-performance ratios of technological innovation related progression of optical technology until now, has shown double rate of that what is to be derived by Moore´s law, describing the time function of progress in technology for the computing industry. As for comparison, the average price of a transistor had dropped in five decades by six orders of magnitude (only). Increasing integration, miniaturisation and mass production are enabled by standardisation and automation of processes, testing and packaging [24].

Aspects in the field of nano-photonics need to cover components, modelling methods, circuits, optical processing of nano-wave signals and broadband systems for a wide variety of applications, such as telecommunications, radar, and fiber-wireless systems, new optical architectures for antenna systems. Techniques for applications such as fiber delivery of nm-waves and high speed fiber-optic links for massive bandwidth, photonic has to converge complementary technologies in the field of interdisciplinary research. These include components for the generation, amplification and high speed detection of photonic signalling. Moreover, constraints for optoelectronic monolithic integrated circuits, also addressing optical links, techniques for signal processing and beamforming for phased array antennas, as well as digital converters, optoelectronic processors and optoelectronics for terahertz frequency range.

Optical signal generation and transmission of high fidelity nanometer waves signals over the fiber is promissing New applications in communications and remote sensing using this technique are expected. Various examples show that coplanar optoelectronic devices can meet ultrahighspeed operation.

Cost factors determine higher data rate of global communication, but new services, enabled by greater bandwidth at declining cost per gigabit-kilometres will initiate additional demand. Driven by avaliable economic returns, utility factor will thus lower overall costs/performance ratios.

4.5 Next Generation Network

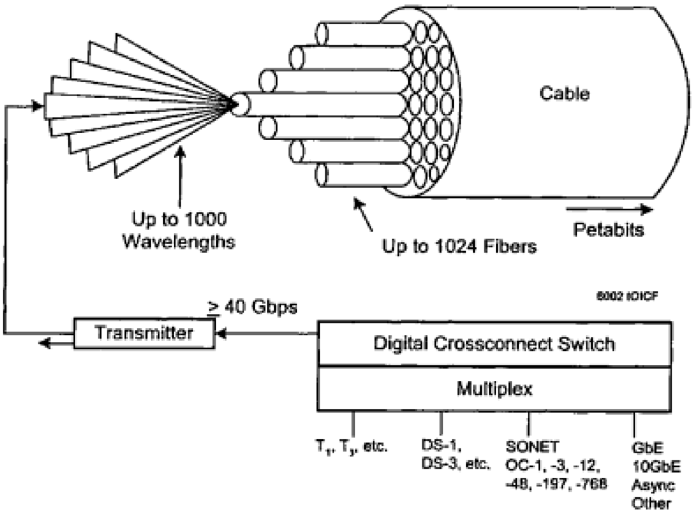


Fig. 4.2: Future Fiber Data Transport (taken from [24])

Projected for 2025, the role of networks is changing from providing distance connection to a platform for services and value creation [27]. Integration of services and applications in networks, prerequisite fusion of computer and communication network. Internet and web-based collaboration change the way business is done, e.g. enterprise process innovation for Supply Chain Management (SCM) or same kind for Customer Relation Management (CRM). Cooperation and efficient use of ultra broadband optical access and broadband mobile access will by its increase soon exceed the critical mass, required to open up new visitas, as cost effective optical network will increase revenues for servicing.

Next generation network in its role as a base for multiple virtual services will be a combination of an all optical core with an adaptive shell, which in its function as an interface for all varieties of signals of different services will transfer those to the core [24].

To cover multiple virtual communities with various services and applications network for:

- In terms of bit rates, protocols and bandwidth required for services, interfaces must be heterogeneous.
- Change of digital hierarchy (SDH) bandwidth pipes to dynamically changing bandwidths.
- Networking software must permit efficient operation.
- Innovation of devices, transmission and node technology are implicated.

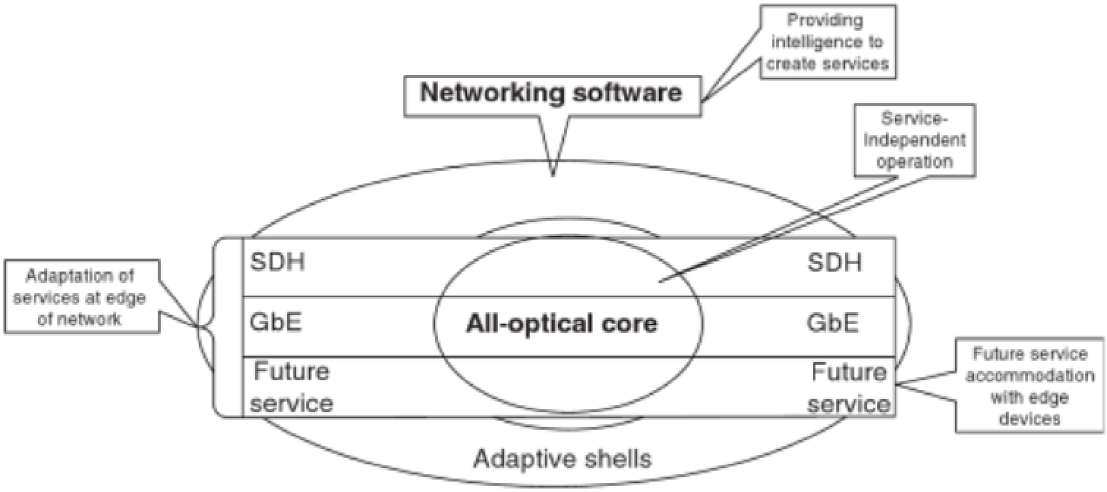


Fig. 4.3: A Vision for Next-Generation Optical Networks (taken from [24])

4.6 Limits of Fiber-Optic Communication Systems

As we have experienced that RF-communications over copper cable (still in use until now) could no more cope the upcoming demand of bandwidth and that microwave technology, still a promising technology until mid 70´s has become obsolete, it is therefore also legitimate to philosophize about the question of limits to optical communication.

Optical path length	1000 km
Fiber type	SSMF
Fiber loss	0.2 dB/km
Nonlinear index	2.6×10^{-20} m²/W
Effective area	80 μm²
Symbol rate	100 Gbaud

Fig. 4.4: Optical Path Parameters (taken from [27])

This event presently seeming in far distance, since rather a poor ratio of capacity in optical network has actually been practically exploited. It is the more surprising that this event could occur even before mid century [27]!

Based on on current fiber capacity estimations and historical data (see table of optical path parameters) and Shannon mathematical approach (see limit table for optimum constellation and optimal coding) assumptions lead to limits that may be reached in the year 2025 !

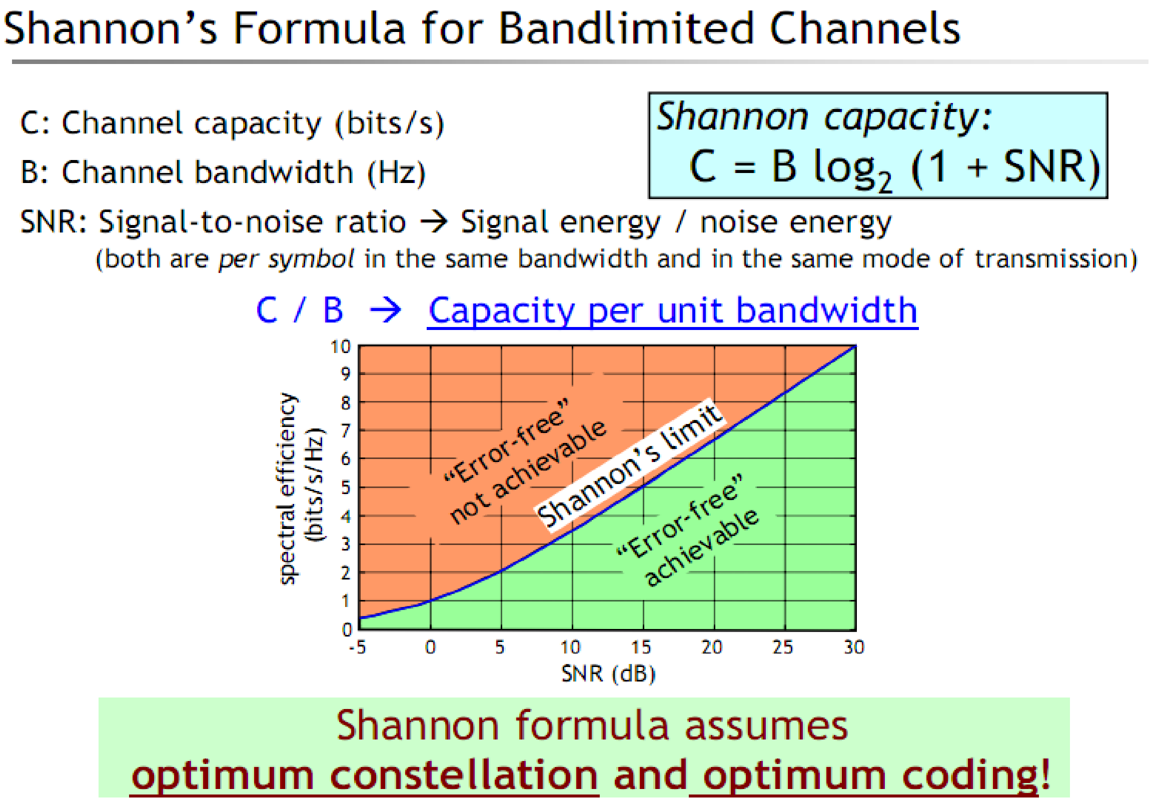


Fig. 4.5: Optimal Constellation and Optimal Coding in Band limited Channels (taken from [27])

In this approach many important open issues remain to be addressed to solve the problem of

- Maximizing fiber capacity in optical networks.
- Achieving capacity requires an array of advanced technologies.

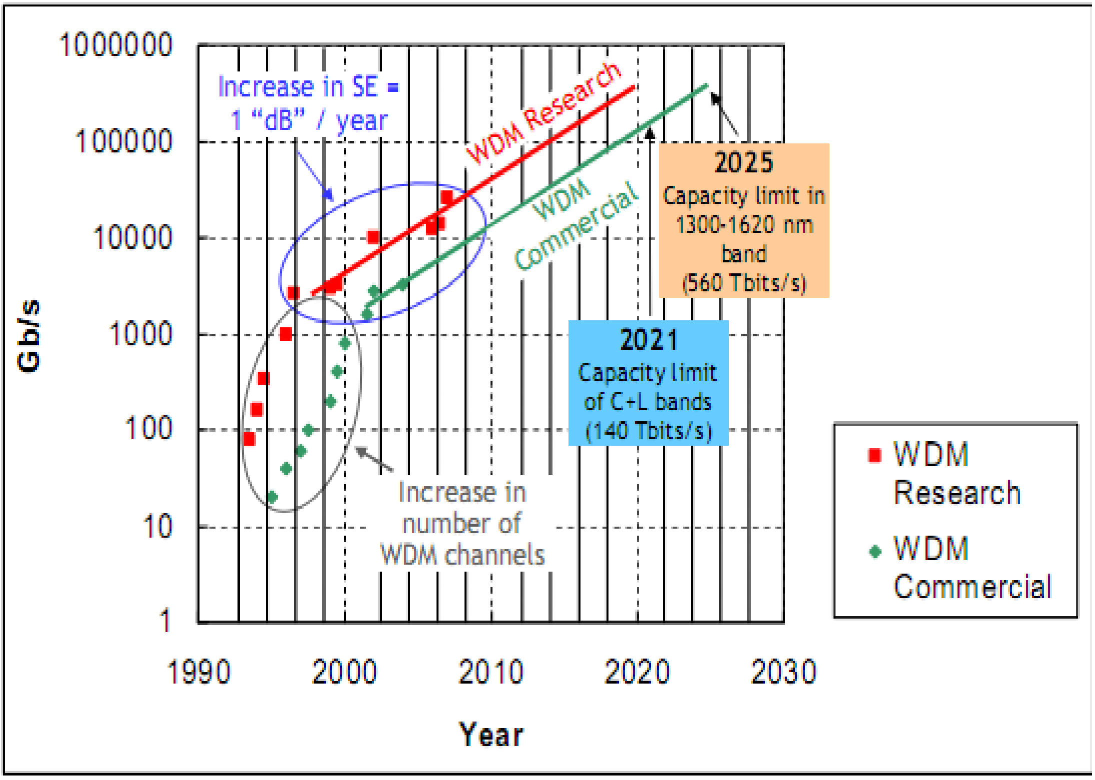


Fig. 4.6: Estimate of Year to reach Fiber Capacity Limits (Based on current Fiber Capacity Estimates and Historical Data) (taken from [27])

5 Conclusion

Demand for rapid communications has been transmitted by optical means even since pre-historical times. In our modern world of electronics it just appeared to us in the late of the 20^{th} century, that electrons are too slow to cope with communications demand.

Photons have taking over the field since the early 80´s as optical components have been put in use for faster and effective communication systems previously dominated by electric current and electrons. Photons which have taken over the tasks of data transfer also serve as the motor of economic development in the 21st century for the domains of rapidly moving, materials processing, chip manufacturing, environment control and material analysis.

Optical networks are the backbones of today's telecommunications systems as they definitely have additional advantages versus traditional RF systems: Optical conductors and contacts made of glass fibres are lighter and more economical, while glass fibres are also interesting for close-range applications. Nano structured semiconductors are one of the major materials used as the basis for these optical components. Futhermore, laser diodes permit high data rates per second.

Optimizations in fiber optic system technologies are going to meet the need of global communications traffic with the use of new materials that may further improve features of optical components impacting present concepts. Optical communication technology is evolving at a fast rate and can deal with new approaches in signal generation, amplification, multiplexing, detection and signal processing. While size of photonic components for future communication systems can be scaled down dramatically along a route of exploring higher system performance

The implementation of RF up/down-conversion techniques for photonic applications has become essential. Current investigations of RF conversion techniques lead to potential reduction of the required bandwidth of the electronic drive circuitry and permission of considerably higher frequencies with the method of WDM RF signal up/down conversion using an optical parametric loop mirror. Moreover, the extension of frequency and bandwidth was attained with the use of agile, high dynamic range photonic converters, realized by optical sideband filtering and the application of a single laser. The allowance of long optical fiber has been accomplished with an RF up- and down-converting optoelectronic oscillator, due to its lower phase noise without spurs. A method of simultaneous realization of photonic frequency up conversion for intermediate frequency (IF) band signals and mm-Wave OFDM signal generation has been demonstrated. And the approach of a Glow Discharge Detector for heterodyne down-conversion lead to the improvement of detection sensitivity.

The presented seamless integrated fiber-wireless system can usher in a new era of ultra high-bit rate (> 100 Gbit/s) wireless communication using W-band. The optical up-conversion of this system is accomplished by optical polarization-density heterodyne beating, while the down-conversion at the W-band Wireless Receiver is realized in two steps. Firstly the down-conversion is performed in analaog domain based on balances mixer and sinusoidal RF signal, and then in digital domain based on DSP.

The Simultaneous broadband optical digital transmission and millimetre RF signals transmission over long-reach WDM-PON is realized by wired and wireless integrated wide-area access network with photonic up- and down-conversion, on the basis of heterodyning.

There is still a great potential in the field of photonic conversion technique research, since its capacity has not been fully exploited and old technologies are being forced out of the market at an extremely fast rate.

Performing optical modules are complex to manufacture and still have a correspondingly high price. Market for fiber optic components is estimated to worth about for 740 billion $ in 2025 worldwide.

Increase of switching speeds are still the issue, but data superhighways for short and long distance communication, as well as between network and computers will evolve when more cost-effective solutions are applied, which could rapidly be overcome by expected synergy in offering multiple cyber services and applications.

The limit, inherent in optical communication could then surprisingly already be reached in mid of our 21st century.

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