

Part I

Introduction to Microwave Photonics

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Microwave Photonics – an Introductory Overview

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In the 1960s, photonics was seen by some visionaries as a possible alternative to microwaves for future high-speed communications. Towards the end of that decade it was not clear which one of these two technologies would eventually prevail for terrestrial telecommunications; indeed, there were trials of a long-distance ‘Millimetric Waveguide’ system by the UK Post Office [1] (which would eventually be abandoned in favour of optical fibre). It was always clear, however, that the two technologies are complementary to one another in many ways, and it is not surprising that they should overlap and merge to form a new interdisciplinary topic – microwave photonics. In this chapter we aim to: (i) define what is meant by the term ‘microwave photonics’, (ii) describe its evolution, (iii) discuss its advantages and limitations and (iv) describe its applications.

1.1 The Roots of Microwave Photonics

Microwave photonics combines technology developed for both the microwave and optical parts of the spectrum (Figure 1.1) [2]. From a historical basis, examples of simple optical communications have existed since ancient times; these relied on human vision to observe signals, such as those generated using semaphore codes by Chappe’s optical telegraph in revolutionary France [3]. The subsequent appearance of the electrical telegraph [4], however, suppressed optical communications for over a century. The first commercially successful transatlantic telegraph cable was installed in 1866 and it would take another century before the publication by Kao and Hockham [5] of a paper outlining how, with suitable reductions of losses in silica, dielectric waveguides in the form of optical fibres could be used for signal transmission.

In addition to the telegraph, researchers in the 19th century also began to examine wireless communications. Despite the demonstration of the photophone in 1880 [6] – the first example of a free-space link in which modulation of a light beam’s intensity and photodetection of it

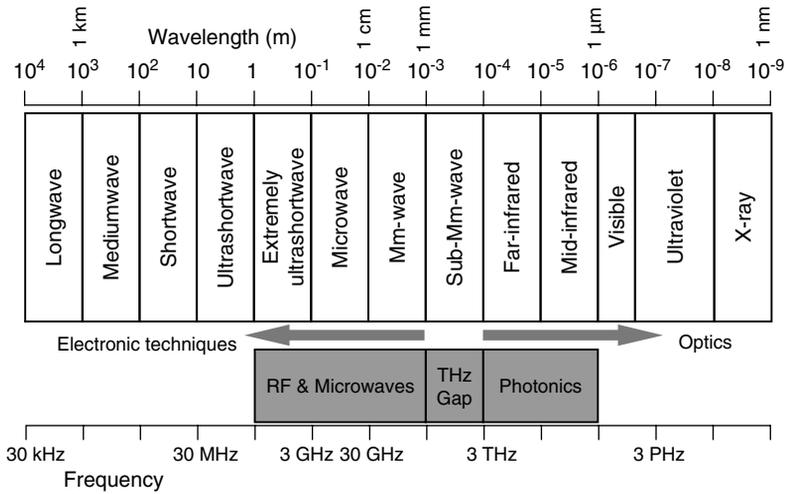


Figure 1.1 The electromagnetic spectrum

was employed for telephone transmission – radio techniques eventually took over and have dominated wireless transmission ever since. The advantages of higher frequencies were recognized early on, and mm-wave transmission was pioneered by Chandra Bose [7] in the 1890s. It was the Second World War and the need for radar, however, that provided the impetus for increased research activity in microwave engineering. Vacuum tubes were the workhorse of microwave electronics for radar systems and then satellite communications, but compound semiconductor technology has since dominated the field of active microwave circuits. In particular, GaAs microwave monolithic integrated circuits (MMICs) have enabled compact and complex circuits of the type needed in applications such as mobile communications and satellite navigation receivers, and the evolving technologies of SiGe and RF CMOS contribute to the continued development of low-cost transceiver technology.

A key component in a communication system is a sinusoidal oscillator. One method of producing coherent oscillations is through stimulated emission, and in the early 1950s the first maser (microwave amplification by stimulated emission) was demonstrated. It was to be the optical maser [8], however, – better known as the laser – that would eventually revolutionize communications (and also many other areas of science and technology). The first solid-state laser was developed by Maiman in 1960 [9] and was soon followed by the first gas laser [10]. Lasing was to be demonstrated subsequently in many other material systems, including semiconductors. If one considers the free-space wavelength of the first laser (ruby), which is 694.3 nm, the corresponding frequency is 432 THz. Even 1% modulation of this frequency still results in a bandwidth far in excess of microwave systems and it was simple calculations such as these that caught the attention of communication engineers in the early 1960s [11]. In spite of the obvious attractions of an optical oscillator, it was still some years away from commercial success and significant progress would have to be made in the many other components needed for an optical communications link. Aside from the practical difficulties of modulating an

optical carrier at high frequencies and then detecting it, there remained the significant problem of guiding it between transmitter and receiver. Proposals for hollow waveguides with periodically located lenses were at one point under serious consideration, but were eventually discarded as impractical.

Looking back at a review of the field from 1970 [12] gives some indication of how there was scepticism as to whether optical communications would supplant microwave and mm-wave communications:

Whether or not there will be a real need for the potentially large bandwidth possibilities in the optical and near-optical region remains something of a question. Even some of the warmest adherents of optical communications laugh at questions about 'payoff'. Some of them assert that they are working with optical devices and systems out of scientific curiosity, because it is fun, because it is intriguing, and other such reasons.

Nilo Lindgren, Optical Communications – A Decade of Preparations, 1970 [12]

The above statement was made only four years after the feasibility of optical fibre was reported in Kao and Hockham's seminal paper [5], and barely a decade after semiconductor laser diodes were demonstrated [13]. Despite the rather cautious nature of Lindgren's analysis, the communications industry viewed the large potential bandwidth of optical communications as being sufficient incentive to pursue the continued development of both optical fibre and semiconductor optoelectronic components. Breakthroughs such as Corning's demonstration of relatively low attenuation in silica fibre [14] and room-temperature operation of laser diodes [15] provided some of the ingredients needed for commercially viable optical links.

Since then, the success of optical fibre communications has more than surpassed what many of its earliest developers would have dared hoped for. Field trials of first-generation systems in the late 1970s using multimode fibre operating at 850 nm had bit-rate distance products of approximately 1 Gb/s-km. This figure-of-merit would go on to double approximately every two years due to the development of a further four generations of optical communications [16]; techniques such as wavelength division multiplexing [17] and soliton transmission [18], both of which were enabled by optical amplifiers [19], meant that long-distance optical fibre links had broken the 1 Tb/s barrier by 2000 (Figure 1.2). Long-awaited developments in fibre-to-the-home (FTTH) are also starting to bear fruit, with a steady evolution from 10 Gb/s Ethernet (10 GbE) through to recent interest in 40 Gb/s and 100 Gb/s Ethernet (IEEE 802.3).

Most optical fibre links are used for digital communications, but due to the high bit rates that are often involved, one must apply analogue microwave techniques to the design of components such as high-speed lasers, optical modulators and photodetectors. In a Mach-Zehnder modulator, for example, it is important to design the electrodes correctly in order to match the phase velocities of the microwave and optical signals. This is a problem in transmission line design. Travelling wave effects must also be considered in certain photodetector designs, while impedance matching techniques play an important part in microwave fibre-optic link design. The study of the interaction of optoelectronic devices with microwave signals is a cornerstone of *microwave photonics*, but the topic is much wider than this as we shall see in the following sections.

Before proceeding to define exactly what 'microwave photonics' means, some mention should be made of the root words. The term 'microwaves' [20] refers to signals in the frequency

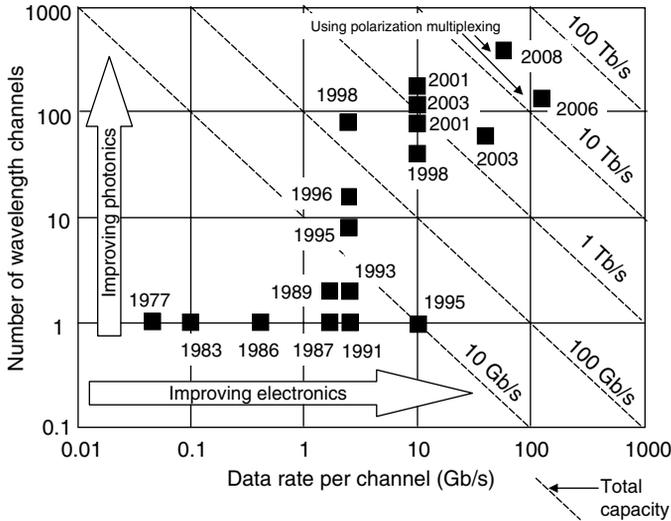


Figure 1.2 Improvements in optical fibre link bit rates and link distance; data points prior to 2004 taken from H. Kogelnik, ECOC'04 (Paper Mo1.1.1)

range between 300 MHz and 300 GHz (while the term ‘mm-waves’ refers to signals with wavelengths of the order of millimetres). ‘Photonics’ [21] is a term that is analogous to electronics, in that it implies control of photons (as opposed to electrons) in either free-space or matter. The photon energies of interest are in the range 0.5 eV to 2 eV, corresponding to free-space wavelengths spanning the visible spectrum as well as the infrared and ultraviolet on either side. One may argue that the term optics could be applied instead, given that we are dealing with the optical part of the spectrum. The fact that multiple terms are available in this field – including optoelectronics, electro-optics and lightwaves – can be confusing, especially given the lack of complete agreement over the precise meaning of these terms.

The fields of electronics and photonics are, at the fundamental physical level, intertwined in any case, since accelerating electrons generate light and light propagating through optical media interacts with dipoles. Whilst electron–electron interaction is strong (with the result that devices such as transistors are feasible), light–light interaction is weak and devices such as lasers and photodiodes rely on electron–photon interaction. In the former electrons control the flow of photons, while in the latter the roles are reversed. According to Saleh and Teich [21], electro-optics is used to refer to optical devices in which electrical effects play a key role (examples include lasers and modulators); optoelectronics refers to devices that are essentially electronic (e.g. diodes) in which optical effects are important (examples include photodiodes). In recent years the term ‘lightwave’ has also proved popular, and the term is to ‘microwave’ as photonics is to electronics. Lightwave technology is commonly used to refer to systems that combine electro-optic and optoelectronic devices with an optical transmission medium (usually optical fibre) in order to transmit and/or process optical signals.

Here we will largely use the word photonics to deal with devices and systems in which photons may be generated, transmitted, controlled or detected. As such, the photons are likely to interact with matter and electrons at various points in the system.

1.2 What is Microwave Photonics?

Microwave photonics has been defined by Seeds and Williams [22] as having two aspects: (i) the study of photonic devices which are capable of processing microwave signals, and (ii) the application of photonic components and techniques to microwave systems.

The first definition will be familiar to those who have worked with high-speed fibre-optic links. This line of research parallels the general field of optical fibre communications, in which significant progress has been made with devices such as lasers, modulators and photodetectors that are capable of handling digital signals up to several Gb/s (or analogue signals up to several GHz). The second definition is a consequence of high-speed optoelectronic components (that were originally developed for the telecommunications industry) being available ‘off-the-shelf’. This has allowed them to be used not only for transmission of analogue microwave signals over optical fibre, but also for the processing of microwave signals in the optical domain. This includes tasks such as filtering and analogue-to-digital conversion, and a major advantage of using photonics in a microwave system is the *huge bandwidth potential of optical fibre* coupled with *low optical loss*.

1.3 Why Use Microwave Photonics?

Microwave and photonic components process electromagnetic waves, albeit in different parts of the spectrum. When combined together in an appropriate sequence, we have a microwave photonic system, and a simple example illustrating the basic concepts is shown in Figure 1.3. This diagram uses terminology borrowed from the lightwave measurements community (see Chapter 10 and also [23]), in which analogue electrical signals in the microwave frequency range are denoted by ‘E’ and optical signals modulated by these same electrical signals are denoted by ‘O’. Conversion between the two domains is carried out by an E/O (electrical-to-optical) transducer at the input and an O/E (optical-to-electrical) transducer at the output end. Between the E/O and O/E stages is the O/O component, which in many examples is optical fibre.

It is the exceptional qualities of optical fibre as a transmission medium which are behind the success of optical communications in general, and which provided one of the primary motivations for microwave photonics research. These include low cost, low weight (typically 1.7 kg/km for fibre as opposed to 567 kg/km for coaxial cable [2]), low cross-sectional area, high degree of physical flexibility, immunity to electromagnetic interference and relatively low dispersion (especially at 1310 nm for silica single-mode fibre) and very low loss (as low as 0.2 dB/km at 1550 nm in terms of optical loss, which is equivalent to just 0.4 dB/km of electrical loss). This last quality of optical fibre is compared with other transmission media in Figure 1.4;

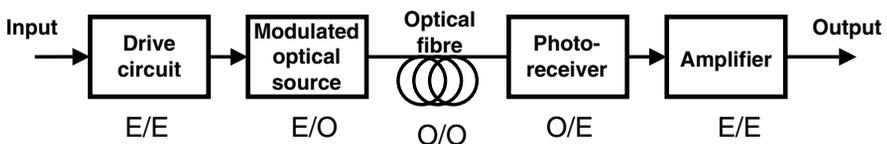


Figure 1.3 Block diagram of a basic microwave photonics link. Reproduced from [23] (© 2008 IEEE)

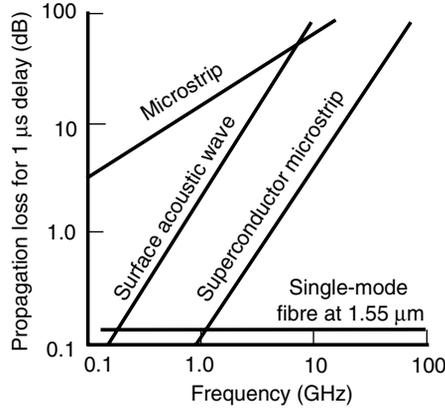


Figure 1.4 Propagation loss characteristics of various delay media (after [102])

the figure shows that an additional advantage of optical fibre is that the loss is flat as a function of microwave frequency. This is because the fractional (i.e. modulation) bandwidth is so small compared to the optical carrier, that is only a minute part of the 1550 nm wavelength window is being used.

From a communications perspective, it is the fibre attenuation and dispersion (along with noise and nonlinearity due to E/O and O/E conversion) which are most crucial in determining signal degradation, but their impact differs according to the application of the link. If digital signals are applied at baseband to the link in Figure 1.3, our primary concern is to recover them at the output at an acceptable BER (bit-error rate – typically 10^{-9}) assuming that the E/O and O/E transducers can handle sufficiently high bit rates. By using Poisson statistics it is possible to arrive at the required O/E receiver sensitivity [24] for a given bit rate, which can then be used (along with knowledge of the E/O source power and fibre loss) to determine the maximum repeaterless transmission distance. The figure-of-merit that is of most interest for digital links, therefore, is the maximum bit rate – distance (BL) product for a specified BER. In addition to attenuation, however, we must also consider dispersion since this will be more deleterious as bit rates increase beyond the so-called attenuation limit (Figure 1.5).

In a digital link, we can tolerate a certain amount of signal degradation as long as the pulse distortion does not result in excessive bit errors at the receiver. We can use optical amplification and regeneration at regular intervals along an optical fibre in order to increase the transmission distance. Moreover, in the electronic domain advanced pulse shaping and error recovery techniques are available. From the point of view of a digital link, therefore, our main aim is to maximize the distance between repeaters and the fact that optical fibre is a superior medium (in terms of attenuation) when compared with free-space, say, is the key factor in the uptake of optical communications over long distances.

When one considers analogue links one must now also factor in the effect of the E/O and O/E transducers. This is because the function of an analogue microwave photonic link is to convey a microwave signal from the input to the output with as little signal degradation as possible, and so we compare it with conventional microwave transmission media. Ideally the link should act as a ‘transparent tube’, in which the output is a delayed replica of the input signal. Looking at

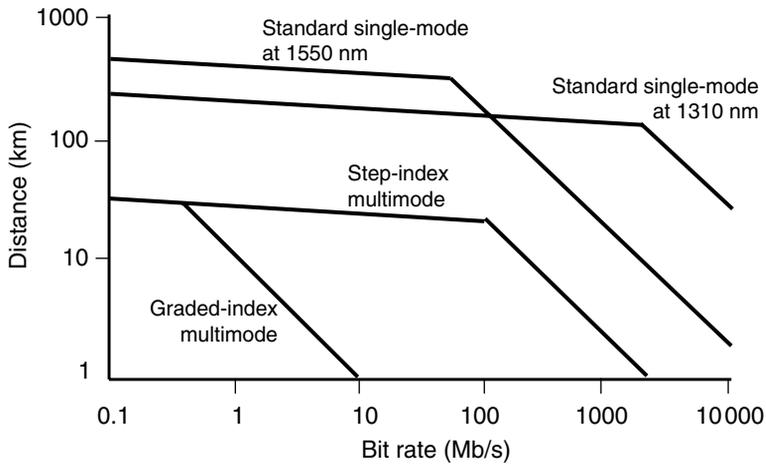


Figure 1.5 Attenuation- and dispersion-limited distance for various optical fibres; the fibres are dispersion-limited at the high bit rate end and attenuation-limited at the low bit rate end

the effect of the optical fibre alone, it certainly outperforms something like microstrip by a substantial margin (Figure 1.4). Not only is its loss lower, but it has a flat frequency response. These two qualities of low transmission loss and large bandwidth capability are the main factors which first persuaded researchers to investigate the use of photonic techniques in microwave systems.

In order for a microwave signal to encounter this low fibre loss, it must first be converted to microwave modulation of an optical carrier and then recovered through photodetection. The E/O and O/E conversion processes introduce a penalty, typically anywhere between 20 dB and 40 dB. When this is included into the link loss calculations, then microwave fibre-optic links only yield lower loss than coaxial cables once they exceed a crossover point, as shown in Figure 1.6. A major goal of microwave photonic link design is the reduction of overall link loss, and to this end improvements can be obtained either through improved O/E conversion [25, 26] or transformer-based matching techniques [27]. In addition to affecting link loss, the inclusion of active E/O and O/E components will also have an impact on three other important performance parameters. The first of these is the overall frequency response of the link, which in turn is affected by the small-signal frequency response (also termed the modulation response when looking at E/O conversion) of the E/O and O/E components. The second is the noise figure; noise is introduced into the link by both the E/O and O/E conversion processes. Finally, E/O (and to a lesser extent O/E) components are inherently nonlinear, and thus they will act to limit the dynamic range of the microwave photonic link.

The above discussion highlights the importance of improving the design and fabrication of E/O and O/E components, along with the development of link design techniques (such as impedance matching) in order to derive the most out of the excellent properties of optical fibre. Later in this book we will discuss the different technologies that are available to achieve these goals, but first we will look at how microwave signals are ‘processed’ by a microwave photonic system.

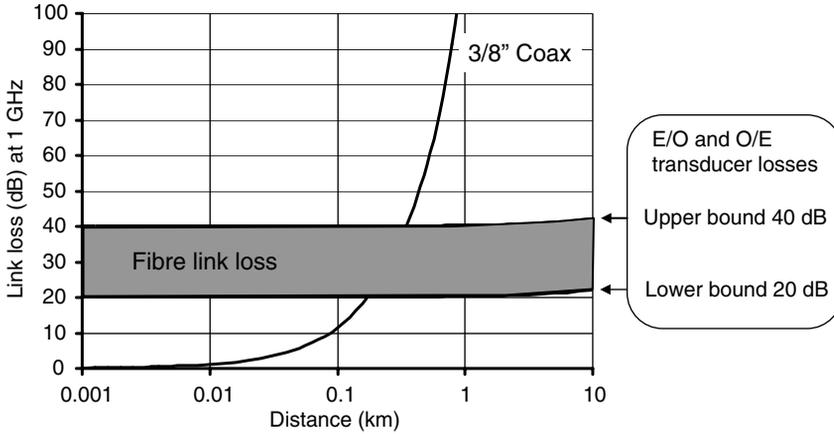


Figure 1.6 Comparison of typical coaxial cable loss compared to standard single-mode fibre; between 20 dB and 40 dB of E/O and O/E transducer losses are included for the fibre

1.4 Anatomy of a Basic Microwave Photonic System

We now examine the E/O and O/E conversion processes in more detail, as shown in Figure 1.7. Many microwave photonic systems use laser diodes for the E/O source module. The laser diode is basically an oscillator, which upon application of a bias current will produce lightwaves with an optical frequency (ω_o) of about 200 THz (assuming we choose a typical emission wavelength such as 1550 nm). If we assume the existence of a perfectly monochromatic laser and also neglect noise, the electric field at a fixed point can be represented by a time-varying complex quantity: $E(t) = E_0 \exp(j(\omega_0 t + \phi_0))$.

In principle, the amplitude ($|E_o|$), frequency (ω_o) or phase (ϕ_o) of the lightwave may be modulated; this is analogous to the situation found in microwave communications. Once modulation has been applied to the lightwave, it will be guided by the optical fibre and be subjected to attenuation, dispersion and possible changes in polarization. At the fibre output, a photodetector is used to recover the original modulation signal. The first stage in a photodetector is a photodiode; this is a square-law device that produces a photocurrent that is directly proportional to the square of the electric field magnitude. This quantity is proportional to the intensity (W/m^2), which in turn is proportional to the optical power.

A photodiode can therefore only directly detect intensity modulation (i.e. modulation of $|E_o|^2$), hence the term direct detection. Most fibre link designs are based on intensity modulation/direct detection (IM/DD) partly to have simple receiver architectures. This is in a loose sense the optical equivalent of the amplitude modulation/envelope detection scheme in radio communications, a scheme which is relatively primitive when compared to the more advanced techniques commonly used in wireless systems, such as those based on phase shift keying. The word ‘loose’ is used in the previous sentence, because if we apply a sinusoidal microwave signal of frequency ω_m to an E/O component, the resulting optical field will contain a central optical frequency ω_o and multiple sidebands at $\omega_o \pm n\omega_m$. The exact

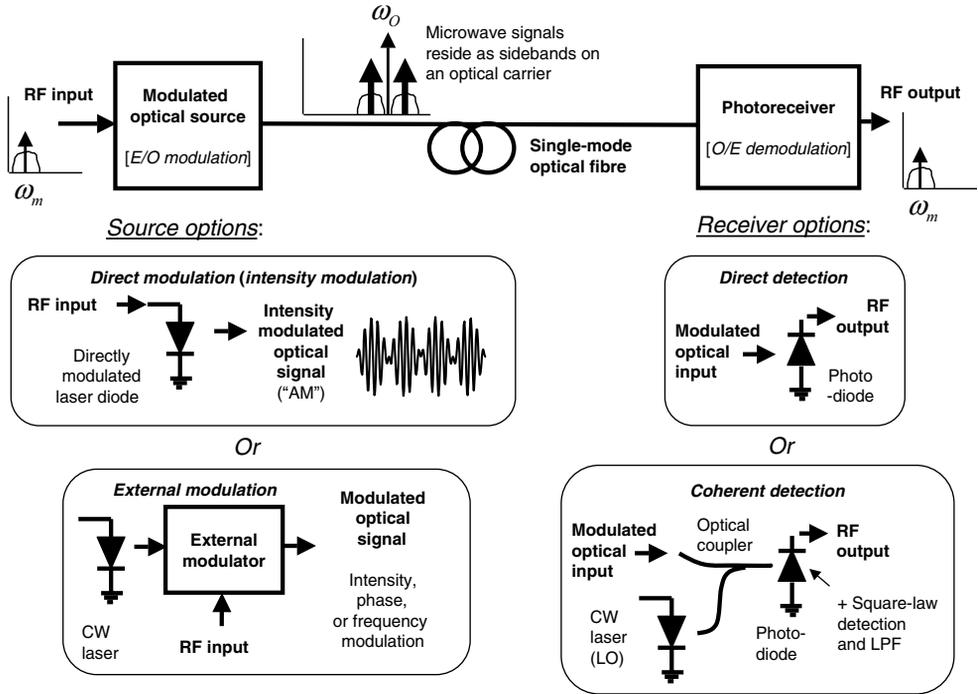


Figure 1.7 Microwave photonic link architectures for direct and external modulation, and for direct and coherent detection. Reproduced from [23] (© 2008 IEEE)

form of the spectrum depends on the E/O device and bias conditions. This is in contrast to the amplitude modulation of radio signals, which normally produces no more than two sidebands.

Intensity modulation can be achieved either directly or externally. Direct modulation of a laser simply means adding a time-varying current which results in the intensity (i.e. optical power) tracking changes in the current. Direct modulation up to about 30 GHz is possible, but one disadvantage of this scheme is chirp, that is the optical frequency is inadvertently modulated. This can be overcome by operating the laser in CW (continuous wave) mode and using an external modulator instead; these are voltage-driven devices and have larger modulation bandwidths (beyond 100 GHz for polymer-based devices). An added advantage of these devices is that in addition to intensity modulation, they can also provide phase and frequency modulation. However, detection of phase and frequency modulation requires coherent photoreceivers using local oscillator lasers. Whilst coherent detection offers improved sensitivity (through the use of high-power local oscillator lasers which effectively amplify the incoming signal), it is more complex to implement than direct detection and places stringent requirements on the linewidth of the source and local oscillator lasers. Moreover, the use of optical amplifiers as pre-amplifiers for photoreceivers means that the sensitivity of direct detection has been improved relative to that of coherent receivers.

1.5 Device Technology

In this section we describe some of the devices which are available to provide the basic functions of E/O and O/E conversion in a microwave photonic system and we briefly discuss O/O components.

1.5.1 E/O Conversion

As mentioned previously, intensity modulation of light can be achieved either through direct modulation of a laser diode or by using a modulator to externally modulate light from a CW laser [28]. External modulation is preferred in ‘high-performance’ applications whereas the advantage of direct modulation is low cost, especially when uncooled laser diodes are used.

1.5.1.1 Directly Modulated Laser Diodes

The advantage of laser diodes is that they are compact and only require a few mA of drive current in order to operate; they also offer a potential route to monolithic integration with a variety of other electronic and photonic structures on the same chip. If we confine our discussion to single frequency signals, then in a directly modulated laser diode (Figure 1.8), the drive current I_L is given by $I_B[1 + m\cos(\omega_m t + \phi_m)]$, where I_B is the bias current and m is the modulation index. We can show that the electric field emitted by the device (if we neglect chirp) has the form:

$$E(t) = E_0 \sqrt{1 + m \cos \omega_m t} \exp(j[\omega_o t + \phi_o]) \quad (1.1)$$

For small-signal modulation $m \ll 1$ so we can use Bessel functions to expand the electric field expression. We can show that this contains multiple frequency components of the form $\omega_o \pm n\omega_m$. In effect the E/O transducer is an up-converter, mixing ω_m onto an optical carrier.

However, the optical intensity will be given by the square of the electric field magnitude. If we square the magnitude of Equation (1.1), we find that the optical output power is of the form $P_0(1 + m(\cos \omega_m t + \theta_m))$ where P_0 is the average power, ω_m is the microwave modulation

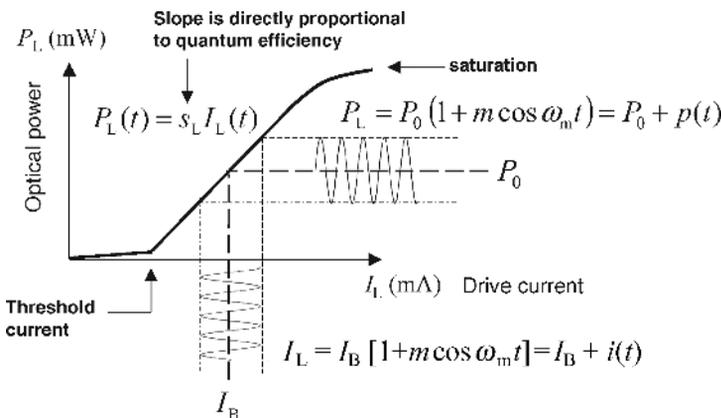


Figure 1.8 Typical light–current characteristic for a laser diode. Reproduced from [23] (© 2008 IEEE)

frequency and θ_m the phase. If we consider the light–current characteristic of a laser diode, the above result makes sense. The light–current ($L-I$) characteristic is a plot of optical output power versus drive current as shown in Figure 1.8. This resembles the DC piecewise-linear $I-V$ characteristic of a diode. Above threshold and below saturation, the $L-I$ characteristic can be approximated very well by a straight line segment with a slope given by $s_L = \delta P_L / \delta I_L$, where s_L is the slope efficiency in W/A. Ideally we want the slope efficiency to be as high as possible but it is fundamentally limited by the quantum efficiency of the laser. Hence, if we ensure that the drive current does not go below threshold or into saturation, the optical power will follow the drive current (Figure 1.8). The ‘DC’ components are related via $P_o = s_L I_B$, where P_o is the average optical power. Although it is not obvious from the $L-I$ curve, the slope efficiency is frequency-dependent. At a given frequency, the sinusoidal components of the current and optical power can be described using phasors, and they are related via:

$$s_L(j\omega_m) = \frac{p_L(j\omega_m)}{i_L(j\omega_m)} \tag{1.2}$$

where $i_L(j\omega_m)$ is the modulation current phasor and $p_L(j\omega_m)$ is the corresponding output optical power phasor. $s_L(j\omega_m)$ is referred to as the intensity modulation response and is an important parameter. Directly modulated laser diodes have a low-pass second-order response which places a limit on the bandwidth they can support, as shown in Figure 1.9. The second-order response is a consequence of the interaction between carrier recombination and photon emission, which in the simplest case is described by a pair of nonlinear ordinary differential equations (the rate equations, as described in greater detail in Chapter 2). These can be solved to determine both the damping factor and the resonance frequency, which in turn influences the small-signal intensity modulation bandwidth. It should also be borne in mind that the bond wire and package parasitics will influence the overall response (usually in an adverse way), so optimization of these is required in high-speed laser diodes.

When considering direct modulation for microwave photonics systems, we therefore have to be aware of a number of performance parameters and device limitations. Two important parameters are the slope efficiency (which will impact the overall link gain as discussed in Chapter 6) and also the bandwidth (which given the fact the O/E transducers generally have very high bandwidths will often be the limiting factor in overall link bandwidth). Limitations of the direct modulation approach include: (i) the inadvertent modulation of wavelength

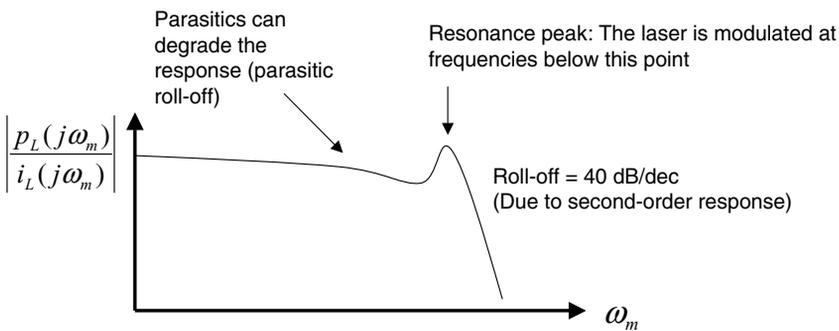


Figure 1.9 Typical intensity modulation response for a laser diode

(the chirp referred to earlier), which when combined with fibre dispersion will lead to signal degradation; (ii) nonlinearity, which can be significant at the resonance frequency (and in severe cases can lead to chaos); (iii) multiple-sideband modulation, which when combined with fibre dispersion can lead to power fading (this depends on the fibre length and the laser wavelength); (iv) relative intensity noise (RIN), which will affect the overall noise figure performance of a microwave photonic system; (v) a differential quantum efficiency which is less than unity, which results in E/O conversion loss; and (vi) perhaps most important of all, lower bandwidth compared to external modulation.

In spite of the above limitations, the simplicity and relatively low cost of direct modulation are very attractive for many applications, and this continues to drive forward research in high-speed laser diodes. We can categorize laser diodes according to device structure, three main types being Fabry–Perot, distributed feedback (DFB) and vertical cavity surface emitting lasers (VCSELs); these are compared in Figure 1.10. We can also classify the laser material according to whether it is bulk, quantum well or quantum dot. Over the years a large body of research has aimed to engineer both the device structure and materials in order to increase bandwidth, improve slope efficiency and also yield other improvements (such as reduced threshold current and temperature sensitivity). The use of multiple quantum wells for DFB lasers has proved particularly successful, leading to increased differential gain and reductions in threshold current compared to bulk devices. Bandwidths in excess of 30 GHz have been demonstrated for InGaAsP quantum well lasers operating at 1550 nm [29] and for distributed Bragg reflector devices [30]. In recent years much effort has been put into quantum dot devices [31], since these lasers promise near zero threshold currents and reduced sensitivity of threshold current to temperature fluctuations. This last feature is important, since it dispenses with the need for temperature control circuits, thereby leading to reduced cost. Devices for 10 Gb/s applications have been reported [32]. The theme of low cost also crops up in the development of VCSELs; here the vertical emission opens up the possibility of on-wafer test and the circular beam profile also simplifies the laser-to-fibre coupling problem. Given the renewed interest of multimode fibre for microwave photonics applications, as discussed later, the VCSEL takes on added significance for the implementation of in-building fibre radio networks for example. Modulation bandwidths of the order of 10 GHz have been obtained at 1550 nm [33].

Significant work has also been carried out with more complex structures to improve slope efficiency (e.g. the gain lever laser [34] and bipolar cascade laser [25,35]). The use of multiple junction laser transmitters [36] is discussed in more detail in Chapter 2. Recently, much work has also been done to extend the modulation frequency performance of laser diodes. Some techniques are narrowband and rely on using external optical cavities with frequency selective feedback in order to enhance the resonant response [37], while an alternative method is based on optical injection locking [38] and this has been used to demonstrate an enhanced resonance frequency of 72 GHz [39]. In this last technique, the free running lasers typically have modulation bandwidths of no more than 10 GHz. By using high optical injection ratios, it is possible not only to achieve resonant enhancement but also to enhance the 3 dB bandwidth, improve the modulation efficiency (by a factor of 10) and reduce the relative intensity noise (to -140 dB/Hz) [38]. Optical injection locking also reduces distortion, leading to enhanced spur-free dynamic range (SFDR). Recent work has focused on cascaded optical injection locking, in which an additional slave laser is introduced [40]. This enables 1.55 μm VCSELs with a free running 10 GHz bandwidth to exhibit up to 66 GHz bandwidth, thus opening up their use in mm-wave fibre radio systems.

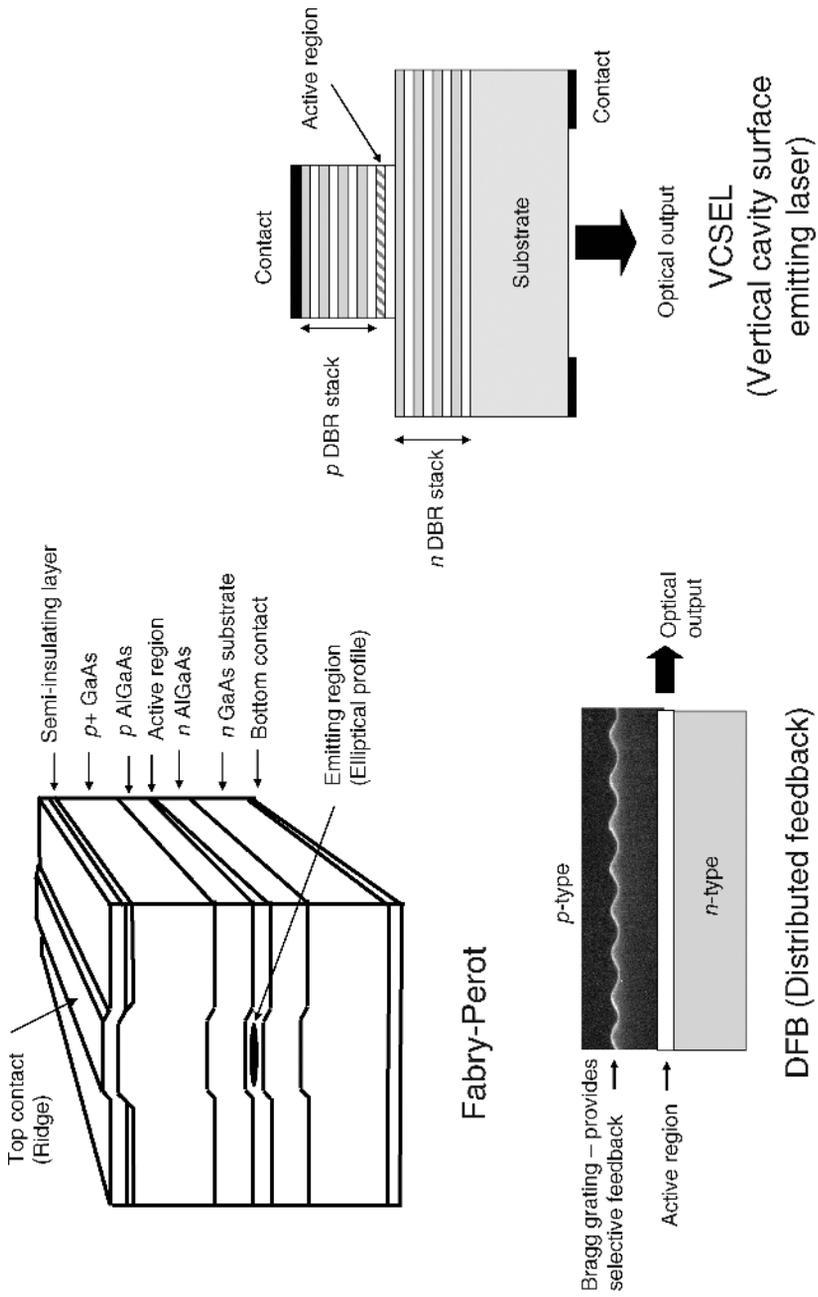


Figure 1.10 Example structures for Fabry-Perot, DFB and VCSEL lasers

1.5.1.2 External Modulation

As implied by the name, external modulation entails the use of an external device (i.e. the modulator) to vary either the intensity or phase of the light emitted by a laser diode emitting a constant power level (CW mode). The obvious disadvantages are the added cost, complexity and increase in the size of the E/O module, but these are accepted in many instances because of the greater bandwidth on offer (especially important for mm-wave applications) and the greater control over which the modulation is carried out, which opens up possibilities such as single-sideband operation. Furthermore, unlike direct modulation, external modulation does not suffer from the problem of chirp.

Many of the performance requirements that were discussed for direct modulation also apply in the case of external modulation, namely the need for high modulation efficiency, large bandwidth and good linearity. There are also some differences, however, the most evident being that external modulators are voltage driven rather than current driven. In addition, they have an optical input (connected to the CW laser) as well as an optical output, and so low optical insertion loss is required. Since the basic effect in an external intensity modulator is varying absorption of the optical input from the CW laser, it is desirable to have high optical power handling capability.

As with direct modulation, a number of material systems and device structures are available. The most successful from a commercial perspective is the Mach–Zehnder structure implemented in lithium niobate, but there are also many examples of electro-absorption modulators (fabricated from III-V semiconductors) and polymer-based devices. A particular advantage of electro-absorption modulators is the possibility of monolithic integration with the CW laser.

The underlying mechanism in lithium niobate modulators is the Pockels (or linear electro-optic) effect in which an electric field (originating from an external drive voltage) induces change in the refractive index, which in turn will lead to a change in phase. When an interferometric structure is used, the phase modulation is converted to intensity modulation. The electro-optic effect is found in crystals such as lithium niobate and gallium arsenide as well as poled polymers.

Figure 1.11 shows the basic structure of a lithium niobate Mach–Zehnder modulator. The basic idea is that an applied voltage can be used to vary the phase shift between the two optical waveguide arms, such that when light is combined from these arms at the output it can vary between a minimum level (corresponding to destructive interference) and a maximum (due to constructive interference). The simplest Mach–Zehnder design is one in which phase modulation is applied to only one of the arms, but it is also possible to have dual electrode designs and these have been used for optical single sideband generation (OSSB) in order to overcome the dispersion penalty which occurs in mm-wave fibre radio systems.

In a similar vein to the analysis carried out for the directly modulated laser diode, we can consider the static transfer characteristic (Figure 1.12) of an external modulator in order to deduce parameters such as the slope efficiency. The approach has several important differences though.

- (i) The actual optical power level (P_o) depends not only on the modulator but also on the power supplied by the CW laser source (P_i); the y -axis is a ratio of powers rather than being absolute power.
- (ii) The x -axis is also a ratio, of the drive voltage V_m to V_π (this being defined as the voltage required for a phase shift of π between the two modulator arms).

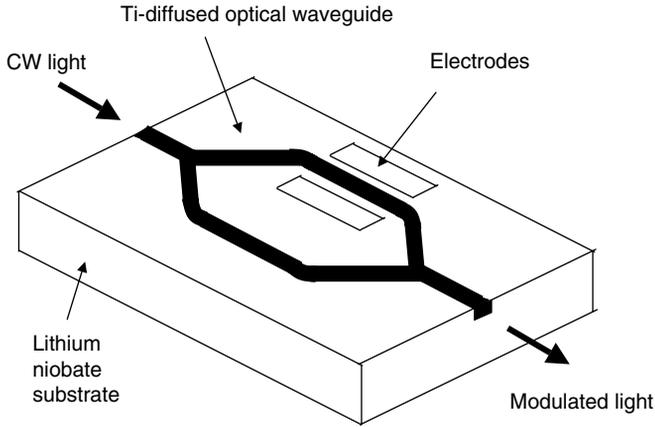


Figure 1.11 Simplified diagram of Mach-Zehnder modulator

(iii) The transfer characteristic is periodic, in principle allowing more choice in terms of choosing the bias point. One suitable bias point is located at $3V_\pi/2$ as shown in Figure 1.12, and if we apply small-signal modulation then excursions in voltage will occur over a quasi-linear part of the characteristic. (It can be shown quite easily that the optimum bias point for maximum modulation efficiency can be located at any odd multiple of $V_\pi/2$.)

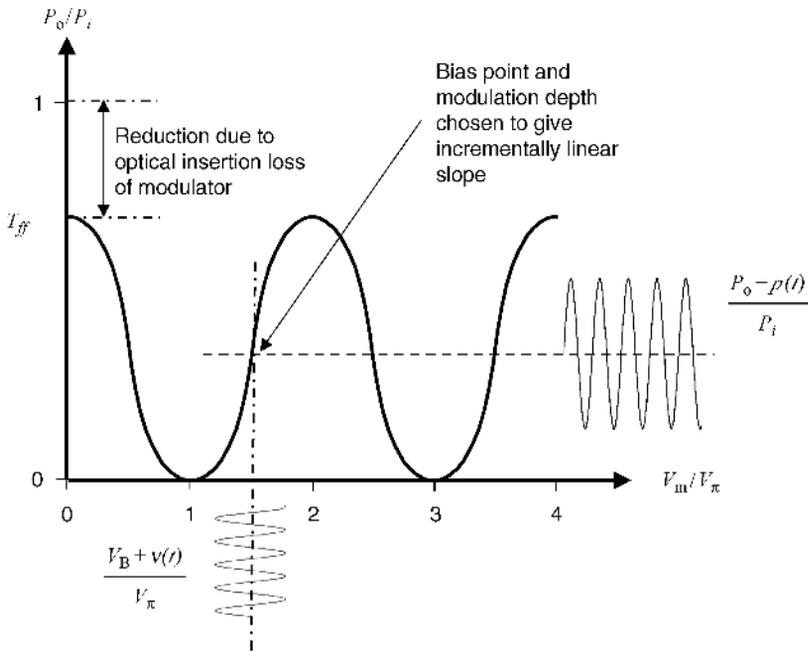


Figure 1.12 Mach-Zehnder modulator transfer characteristic

As for the case of the directly modulated laser diode, we are interested in the slope of the characteristic in the vicinity of the bias point. The important difference here is that the points (i) and (ii) above indicate that the slope will depend on both V_π (which crudely speaking can be thought of as analogous to the threshold current in a laser diode, in that it is a property of the device) and P_i (which is in effect an external control parameter). For directly modulated laser diodes, the slope efficiency is essentially dictated by the device's differential quantum efficiency alone.

The transfer characteristic for the Mach–Zehnder modulator is given by:

$$\frac{P_o}{P_i} = \frac{T_{ff}}{2} \left[1 + \cos\left(\frac{\pi V_m}{V_\pi}\right) \right] \quad (1.3)$$

where T_{ff} is the optical insertion loss of the modulator when it is biased for maximum transmission (e.g. at zero volts). If we now apply a bias voltage of $V_B = nV_\pi/2$ (where n is odd) and a small-signal modulation component given by $v_m(t)$, then linearization of Equation (1.3) around the bias point will yield:

$$\frac{P_o}{P_i} = \frac{T_{ff}}{2} \left[1 + \cos\left(\frac{\pi(V_B + v_m(t))}{V_\pi}\right) \right] \approx \frac{T_{ff}}{2} \left(1 \pm \frac{\pi v_m(t)}{V_\pi} \right) \quad (1.4)$$

from which the slope efficiency (in W/V) is obtained as:

$$s_M = \frac{dP_o}{dv_m} = \frac{T_{ff}\pi}{2V_\pi} P_i. \quad (1.5)$$

Equation (1.5) shows one advantage of using an external modulator, namely that by increasing the CW laser power P_i we can increase the slope efficiency of the external modulation process. In other words the external laser acts as a 'bias' which can be used to control modulator efficiency, and in turn the gain of the microwave photonic link. Indeed, this approach has been used to demonstrate link gain without any other optical or electronic amplification being used. The above equation also illustrates one of the key issues of modulator design, namely the desire to reduce the drive voltage V_π so as to bring it within the range available from drive electronics (ideally below 3.5 V). One technique for doing so is to increase the microwave-optical interaction length (i.e. the electrode length), but this demands reductions in electrode and optical waveguide loss, and wafer size will ultimately place a limit on length. This can be overcome by using folded structures [41].

A further issue in modulator design is that of velocity matching, and as such this represents an excellent case study of classical microwave engineering techniques being used to optimize the performance of a microwave photonic device. In travelling-wave modulators, the electrodes are designed to act as microwave transmission lines, with the microwave signals propagating in the same direction as the optical signals (the optical waveguides being parallel with the electrodes). One advantage is that these devices are not capacitance limited in terms of their frequency response, thus enabling relatively long electrode designs (typically thousands of wavelengths [28]). It then becomes imperative that the phase velocities of the microwave signals and optical signals are matched to one another, and this should be done over a range of frequencies. In lithium niobate, the microwave signal has a lower velocity than the optical signal and so it must be speeded up – usually by appropriate modification of the transmission line capacitance per unit length, this being achieved with a silicon dioxide buffer layer. Conversely,

in GaAs and InP devices this situation is reversed and the microwave signal needs to be slowed down; this can be achieved through periodic capacitive loading of the electrodes. The other transmission line issue for Mach–Zehnder modulators relates to having to avoid standing wave formation on the electrode structure due to reflections from impedance mismatches. Ideally the characteristic impedance of the electrodes should match that of the driver electronics.

As was the case for directly modulated laser diodes, a Mach–Zehnder modulator will in general produce multiple optical sidebands when modulated by a microwave sinusoid, leading to terms in $\omega_o \pm n\omega_m$. This is a consequence of the nonlinearity of the E/O conversion process. However, through appropriate bias and modulation conditions, it is possible to suppress higher order sidebands, leaving a carrier plus an upper and lower sideband, namely ω_o and $\omega_o \pm \omega_m$. It is also possible to generate a single sideband as mentioned above, and this has uses in optical filter measurements (Chapter 10) and mm-wave fibre radio (Chapter 7).

Extensive work has been done on linearization schemes for lithium niobate Mach–Zehnder modulators. One of the motivations for this is to improve the dynamic range of microwave photonic links. The general approach is to connect two modulators together (either in a cascade or in a ‘dual signal’ arrangement) and select appropriate bias points such that the composite device behaves more linearly than either one of the individual modulators [42]. One of the difficulties of these approaches is the susceptibility to tight tolerance requirements and the increased optical losses due to the use of two modulators rather than one. A comparison of different schemes in terms of their bandwidth is available in [43]. Recently a new design of Mach–Zehnder has been proposed in which linearization is performed by using phase control and a resonator on one of the modulator arms, leading to reduced optical losses compared to earlier techniques [44].

The one disadvantage of lithium niobate as a material is that it cannot be integrated with the laser diode source, a fact which has motivated the investigation of III-V semiconductors, including both GaAs and InP. Semiconductor-based modulators are also more compact, but the linear electro-optic (Pockels) effect is weaker than that in lithium niobate and there tends to be a poor overlap between the optical mode and the applied electric field. Furthermore the refractive index of InP, for example, is relatively higher (3.5) than that for silica optical fibres, all of which leads to increased fibre-to-fibre insertion loss for these modulators (typically 10 dB). Nevertheless, some impressive results have been achieved, including demonstrations of low drive voltage (0.45 V for a GaAs Mach–Zehnder modulator for an estimated bandwidth of 50 GHz [45]) and demonstrations of 80 Gb/s modulation (for an InP modulator with capacitively loaded electrodes [46]).

Another material system that has attracted much interest is organic polymers, the primary motivation being the potential for low-cost manufacturing [47]. These materials can be endowed with an electro-optic effect via high-temperature poling, resulting in a Pockels coefficient (r_{33}) as high as 320 pm/V at 1550 nm [48], as opposed to 31 pm/V for lithium niobate. Another parameter that works in favour of electro-optic materials is the fact that the dielectric constant for the microwave signals is approximately equal to the square root of the refractive index in the optical range, meaning excellent velocity matching between microwave and optical signals on the same substrate. This removes the need for techniques such as capacitive loading of electrodes and also results in extremely wideband performance. Bandwidths in excess of 100 GHz were demonstrated some time ago [49], while drive voltages in the sub-volt region have recently been demonstrated at 1550 nm [50]. A further benefit of the polymer approach is that it lends itself to hybrid packaging of both microwave and optical

components on the same platform [51]. In spite of all these advantages, polymer modulators have been beset by a number of difficulties, including optical power handling capability and long-term bias point stability. Research work continues on refining the technology [52].

In addition to being able to exploit the electro-optic effect in semiconductor materials in order to form Mach–Zehnder modulators, it is also possible to use the electro-absorption effect. Electro-absorption can occur in both bulk semiconductors and quantum well structures; for the former it is referred to as the Franz–Keldysh effect while in the latter it is called the quantum confined Stark effect (QCSE) [53]. Several examples of multiple quantum well (MQW) electro-absorption modulators (EAMs) have been reported. A typical EAM structure is one in which MQWs are embedded within the intrinsic region of a reverse-biased PIN diode, which being relatively thin (of the order of $0.1\ \mu\text{m}$) means that only a few volts will result in very large electric fields. QCSE is based on the concept of excitonic absorption, which in a MQW is stronger than in bulk materials and has a sharp spectrum at wavelengths corresponding to the bandgap energy. Application of reverse bias, however, will lead to a reduction of excitonic absorption and broadening of the spectrum, as the exciton absorption line shifts to longer wavelengths [54]. The end result of these physical effects is the set of absorption spectra shown in Figure 1.13. Because the shift of absorption spectra with varying bias occurs over a relatively narrow window of wavelengths, precise alignment between the wavelength of the CW source laser and the EAM is required. EAMs have been successfully demonstrated at frequencies as high as 60 GHz [55], and the envisioned application here would be 60 GHz fibre radio picocells. The fact that EAMs can be monolithically integrated with lasers points toward the possibility of low cost, although it should be pointed out that packaging issues still need to be resolved as does sensitivity to changes in temperature and/or bias voltage.

1.5.2 O/E Conversion

An O/E transducer performs the reverse of E/O conversion, that is it converts incoming modulated light into corresponding variations of current. The term photodetection is commonly used. However, incident modulated light can also interact with electronic devices such

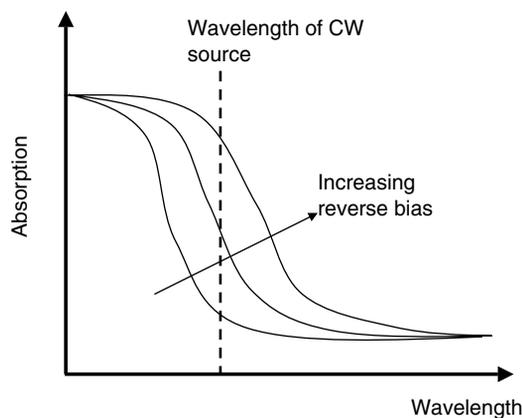


Figure 1.13 Absorption spectra for EAM; as the bias is adjusted the absorption will vary for a given wavelength as shown

as diodes and transistors, a field known as optical control of microwaves; an excellent review can be found in [56]. Optical control can be used to perform functions such as amplifier gain control, oscillator tuning and optoelectronic mixing [57]. Although a large body of work exists on the modelling, characterization and use of optically controlled microwave devices, it is a niche area and we will concentrate on discussing high-speed photodetection instead.

1.5.2.1 Photodetection

Just as the requirement of high bandwidth and conversion efficiency is demanded of E/O components for microwave photonics, the same is true for photodiodes although in this case we refer to responsivity (in A/W) as opposed to slope efficiency (in W/A or W/V) when considering conversion efficiency. The DC responsivity is given by the slope of the characteristic shown in Figure 1.14, and is defined as:

$$R = \frac{I_P}{P_I} = \eta \frac{q\lambda}{hc} \quad (1.6)$$

where I_P is the photocurrent generated in response to the incident optical power P_I , η is the quantum efficiency, which is limited to a theoretical maximum of unity, h is Planck's constant, c is the speed of light, q is the electron charge and λ is the operating wavelength. The incremental responsivity, which will be frequency-dependent, is given by $R(j\omega) = i_P(j\omega)/p_I(j\omega)$. Here we are dealing with the modulation component of both the current and optical power. In a high-quality photodiode the responsivity will have a fairly flat frequency response.

Often there is also a need for high-power handling capability, which originates from the fact that externally modulated systems have increased link gain if higher powers are used for the CW laser driving the modulator. In addition, it is required to avoid optical reflection from the device input in order to maximize the optical power entering the active region, so antireflection coatings are often used for this purpose.

Two main classes of photodiode exist – lumped element designs (which include vertically illuminated photodiodes and edge coupled waveguide photodiodes) and distributed designs (such as travelling wave photodiodes and periodically loaded travelling wave photodiodes). These are illustrated in Figure 1.15.

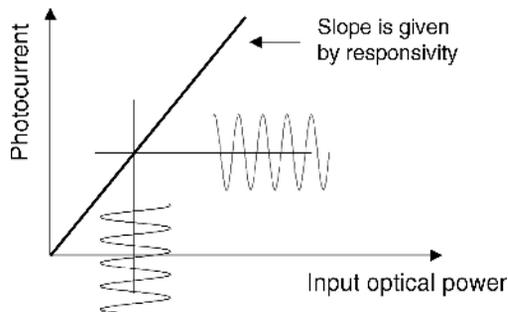


Figure 1.14 Photodiode transfer characteristic. Reproduced from [23] (© 2008 IEEE)

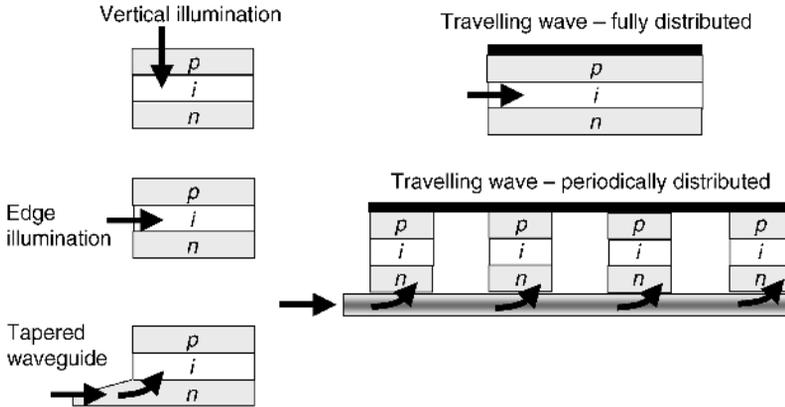


Figure 1.15 Examples of lumped (on the left) and distributed (on the right) photodiodes

Before discussing these various device types, brief mention should be made of the avalanche photodiode (APD), which unlike the structures in Figure 1.15 offers internal gain and hence improved receiver sensitivity without the need for external amplification. In addition, for high enough multiplication factors (i.e. gain) there is an improvement in the signal-to-noise ratio (SNR) that becomes shot-noise limited provided there is little excess noise [24]. One limitation of APDs is that there is a fixed gain–bandwidth product resulting from the fact that for higher multiplication factors there is an increased time required in order for the avalanche to build up within the photodiode structure [58]. This means there is a trade-off between bandwidth and gain. Gain–bandwidth products in excess of 300 GHz have been demonstrated in waveguide APDs [59], hence such devices are restricted to a few tens of GHz at most if even modest gains of the order of 10 are required. Moreover, the APD structure is notorious for temperature sensitivity and the avalanche gain process requires higher operating voltages compared to photodiodes without internal gain.

The device that is most commonly used in microwave photonic applications is the PIN, which has a simple structure – it is a junction diode with an intrinsic layer between doped p and n layers, hence the name PIN [60]. The simplest PIN is a vertically illuminated structure in which light enters the upper layers of the device and is absorbed as it travels through the structure, generating electron-hole pairs in the depletion region. The depletion region extends mostly over the intrinsic region, being formed by a reverse bias voltage. The generated electron-hole pairs are then swept by the bias electric field to the device contacts to produce a photocurrent. One advantage of the vertical illumination scheme (also known as surface illumination) is the ease with which light can be coupled into the device. A disadvantage is the trade-off between conversion efficiency and transit-time limited microwave performance.

The transit time is defined as the time taken for the photogenerated carriers to reach the device contacts and it is determined by both the width of the active absorption region and the saturation velocity in the semiconductor material. The thickness of the active region will also determine how much optical power is absorbed, with this being given by:

$$P(d) = P_0(1 - e^{-\alpha(\lambda)d}) \quad (1.7)$$

where P_o is the incident optical power, $P(d)$ is the optical power absorbed in a distance d and $\alpha(\lambda)$ is the optical absorption coefficient. It is assumed here that there is no optical reflection off the device surface. Equation (1.7) clearly indicates that for improved responsivity the device must be thick enough to absorb a large fraction of the incident optical power, but this then leads to increased transit time and hence reduced bandwidth. The maximum bandwidth–efficiency product for single-pass surface illuminated PIN photodiodes is of the order of 30 GHz [61]. It should also be remembered that device parasitics will affect the frequency response and must therefore be minimized, and the lumped nature of the PIN device leads to an RC time constant which can become an issue if the area of the active region is relatively much bigger than the thickness, leading to increased capacitance. In addition to bandwidth, it was mentioned earlier that power handling capability is important. The space charge effect [62] limits the extent to which optical input power can be increased before saturation, and therefore increased nonlinearity occurs.

One technique for overcoming the bandwidth–efficiency limitations of the vertically illuminated PIN is to try to increase the distance over which photons travel through the absorption region in order to maximize optical absorption, whilst keeping the distance that the electron-hole pairs travel as small as possible to minimize the transit time. This may be achieved through creating a resonant optical cavity in order to set up multiple passes of the optical signal through the active region [63], but the resonance leads to wavelength selectivity thus making these devices of more interest for use in wavelength division multiplexed (WDM) systems.

An alternative way of increasing optical absorption and reducing the transit time impact is to use edge-coupling, thus allowing the optical input to enter the intrinsic region directly and to propagate orthogonally to the electric field. In effect the structure becomes an optical waveguide, allowing the design of long but narrow absorption regions which ensure that a large fraction of the input power is absorbed whilst maintaining low transit times [64]. Waveguide photodiodes with bandwidths in excess of 100 GHz have been demonstrated [65], and typical bandwidth–efficiency products for these devices are about 55 GHz [66].

The waveguide photodiode has two disadvantages. First, the thickness of the active layer is often less than 1 μm , leading to a significant reduction in coupling efficiency between the photodiode and single-mode fibre. This can be mitigated to some extent by using tapered fibre or by fabricating devices that have doped optical guiding layers around the absorption region [60]. Secondly, the ‘long and narrow’ topology creates a capacitive region with a large area-to-thickness ratio, resulting in increased capacitance which causes an RC time limitation once device contact and load resistances are taken into account.

The PIN structures discussed above are lumped element approaches. In order to eliminate the limitation of the RC time constant and to improve impedance matching, distributed designs were proposed in the early 1990s [67–69]. These are commonly known as travelling-wave photodetectors [70–72] and they are a natural evolution of the edge coupled waveguide PIN structure discussed above. In this case, in addition to the optical waveguiding mechanism, the device contacts are engineered to support microwave travelling waves; the approach is similar to Mach–Zehnder travelling wave modulators in that it is another example of transmission line effects in microwave photonics. Coplanar waveguide is typically chosen which supports a quasi-TEM mode; the transmission line parameters are determined by the device capacitance and the contact strip inductance. Absorption of optical power occurs in a distributed manner along the length of the device, setting up a travelling wave on the electrodes as it does so (Figure 1.16). Such a device is no longer limited by RC effects but by the velocity mismatch

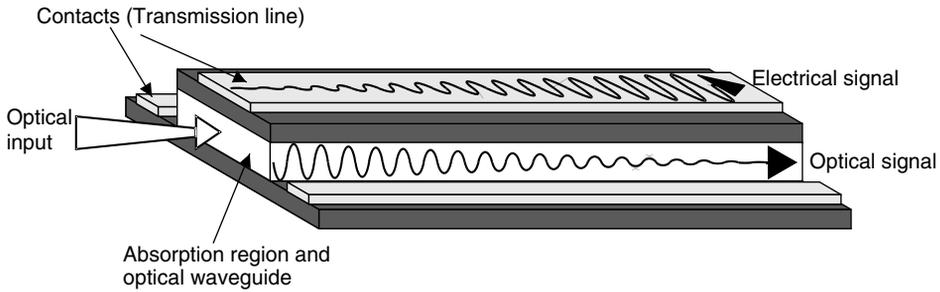


Figure 1.16 Distributed effects in a travelling wave photodetector

between the optical group velocity and electrical phase velocity [60]. When velocity matching is achieved, then long device lengths compared to waveguide photodiodes are possible in principle. The fact that the absorption volume is increased also means that these devices will saturate at a higher power level [73].

A large variety of travelling-wave photodiodes have been demonstrated and exhibit excellent performance. Bandwidths in excess of 500 GHz have been reported for PIN based devices [66], but structures based on metal–semiconductor–metal (MSM) [74], Schottky [75] and phototransistor structures [76] have also been published. In contrast to the other structures, the phototransistor-based travelling wave photodetector provides electrical gain as high as 35 at DC [76]. Recent work [77], however, indicates that the carrier spreading occurring in the base layer of a heterojunction phototransistor travelling-wave structure prevents independent longitudinal operation of the device in response to a position-dependent signal. The extent of the spreading leads to an effective minimum area over which a lumped capacitance limitation still remains. One method for overcoming this problem is to move away from a fully distributed topology to one which is analogous to a microwave travelling-wave amplifier, that is to use a periodically distributed photodetector. The theory of these structures is well known [69] and a variety of approaches to its implementation have been reported, including the use of multimode interference (MMI) couplers [78]. An added advantage of the periodically distributed photodetector is that it can handle higher optical powers.

An alternative approach to handling high optical powers, that also offers high electrical output power is the uni-travelling-carrier (UTC) photodiode [79,80]. Applications of InP-based UTC photodiodes include optical generation of high-power mm-wave signals via heterodyning [81]. The basis of the UTC structure is that of a travelling-wave photodiode, but here the optical waveguide and absorption functions are physically separated. Optical waveguiding occurs in the n layer whilst absorption occurs in the p layer. In this way, the optical power absorption still occurs over an extended region, but the photogenerated current consists solely of electrons—hence the term uni-travelling-carrier. The major advantage is that electrons are faster than holes in materials such as InP, leading to potentially high bandwidths as well as high saturation powers.

1.5.3 O/O Components

The broad bandwidth of optical media is a major driver for microwave photonics, and so we will briefly discuss some O/O components suitable for microwave photonics. The main one is

optical fibre, and many of the microwave photonic systems reported in the literature use standard single-mode fibre and associated components (such as Bragg gratings, circulators, couplers, optical amplifiers and WDM multiplexers). A major advantage of single-mode fibre is the low loss of 0.2 dB/km at 1550 nm, but one also needs to be aware that signal degradation due to chromatic dispersion, polarization-mode dispersion and nonlinearity may need to be considered. If one considers intensity modulated light then, as argued earlier, this can be considered analogous to amplitude modulation. As the optical carrier and its upper and lower sideband propagate through the fibre, dispersion will introduce a phase shift between these components [82], leading to periodic power fading [83] with distance as shown in Figure 1.17. Optical single-sideband modulation can mitigate against this fading, and this can be used to implement WDM-based fibre-radio systems as described in Chapter 7. However, one must then be wary of cross-phase modulation due to optical nonlinearities, which leads to crosstalk between WDM channels [84].

In recent years, multimode fibre has begun to be considered for microwave photonics [85], despite it having a relatively low bandwidth–distance product of 500 MHz.km. This interest is due to the potential low cost of multimode fibre systems, the fact that most installed in-building fibre is multimode and the use of lasers rather than LEDs, with the subsequent demonstration of links operating up to 20 GHz [86]. Given that multimode dispersion can be thought of as equivalent to a transversal optical filter, its transfer function exhibits fading that is reminiscent of multipath fading in wireless systems. Hence orthogonal frequency division multiplexing (OFDM) techniques developed to combat multipath fading for wireless systems have been investigated for multimode fibre radio [87].

Although many microwave photonic systems use passive fibre components, mention should also be made of active O/O components, namely the erbium-doped fibre amplifier (EDFA) and the semiconductor optical amplifier (SOA). The latter is of interest because of the potential to integrate it with E/O and O/E devices, while the former is better suited for splicing into fibre

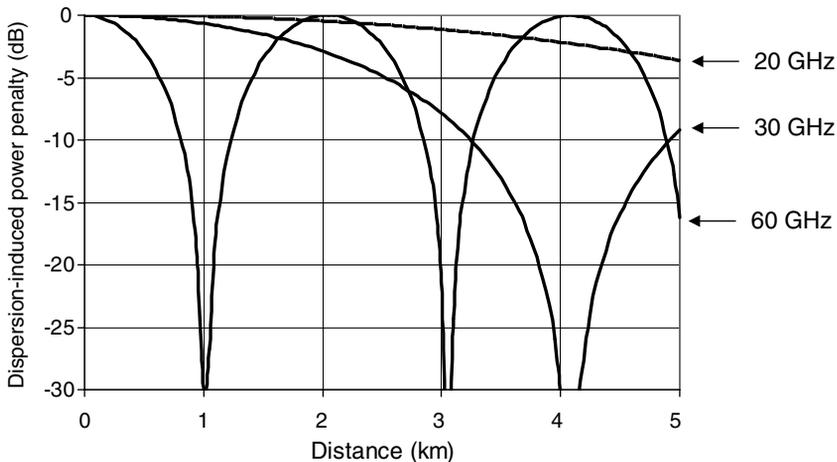


Figure 1.17 Dispersion-induced power fading for standard single-mode fibre at 1550 nm; curves obtained using method described in [83]

systems. A number of microwave photonic filters make use of EDFAs, while both EDFAs and SOAs have been proposed for relatively short fibre links as a means of compensating for E/O and O/E conversion losses. In this second case, optical power levels are relatively high, forcing the amplifier to operate in the gain saturation region. It has been shown theoretically and experimentally that the small-signal microwave frequency response for this mode of operation in an SOA is quasi-high-pass [88].

1.6 Applications of Microwave Photonics

There are a large number of systems and devices that can be said to involve microwave photonics. The main system functions can be divided into: (i) transport of microwave and mm-wave signals over optical fibre (discussed in Chapter 6); (ii) filtering and processing of microwave signals in the optical domain (discussed in Chapter 7); (iii) generation of microwave, mm-wave and THz signals using photonic techniques (discussed in Chapters 4 and 5).

These three areas in turn can be subdivided into specific applications including: radio over fibre (Chapter 7), antenna remoting for radar systems, antenna beam forming, local oscillator generation for radio astronomy arrays, and THz spectroscopy. Since Chapters 4 to 10 deal with many of the above applications in detail, we will simply provide a brief overview here.

1.6.1 Signal Transport

The use of optical fibre for transmission of microwave signals is often advocated due to the advantageous properties of the optical fibre itself [89]. These include low losses, good dispersion management (over the relatively short distances used in some applications), flexibility and immunity to electromagnetic interference. Moreover, the ability to first modulate and then detect modulated light for microwave modulation frequencies up to a few tens of GHz means that such links find applications in the remote location of antennas and radar signal processing, for example. The basic architecture follows the scheme in Figure 1.3. Key parameters of interest are: link gain, noise factor and spur-free dynamic range. A recent review of analogue links by Cox *et al.* [89] points to a number of requirements for E/O and O/E devices in order to enable higher link gain, lower noise and a wider SFDR. These include (i) directly modulated laser diodes with greater slope efficiency, bandwidth and lower relative intensity noise, (ii) CW lasers with higher output power and lower RIN, (iii) external modulators with lower V_π and higher power handling ability, and (iv) photodetectors with higher responsivity, bandwidth and saturation power.

When a microwave signal is transported over fibre, the resulting link is often termed as being analogue in order to distinguish it from the digital links used in telecommunications. It is possible, however, to digitally modulate a microwave signal before transmission over an ‘analogue’ link and so Cox *et al.* distinguish between an analogue and digital optical link as follows. An analogue link involves small optical modulation depths, thus ensuring small-signal operation of the E/O and O/E devices, whereas a digital link relies on on–off keying that may involve modulation depths close to 100%.

Perhaps the simplest signal that can be transmitted over an analogue link is a sinusoid, and there are several applications for distribution of RF, microwave and mm-wave carriers. A high

profile example is the development of fibre networks for radio astronomy facilities [90] such as SKA (the Square Kilometre Array based in Australia) and ALMA (the Atacama Large Millimetre Array based in Chile). ALMA will consist of over 60 12-metre parabolic antennas which can interferometrically detect signals between 27 GHz and 938 GHz [91]. This large frequency range is spanned by 10 bands, and the low noise heterodyne receivers at each antenna each require a local oscillator which is generated optically. The local oscillator signals are then distributed via a fibre network, which must accommodate a maximum antenna separation of 25 km. In this particular application, an optical fibre distribution network offers numerous advantages. Apart from the low loss and large bandwidth provision, the use of fibre also allows a single LO reference to be located at a central office, removing the need for individual LO units at each antenna. This is a feature that also appears in the radio-over-fibre networks (Figure 1.18) discussed below. In addition to the distribution of local oscillator signals, both fibre radio and radio astronomy arrays have a requirement for data transmission over fibre, and the different schemes for sending data over analogue fibre-optic links will be outlined in Section 1.6.4.

1.6.2 Signal Generation

The ALMA project represents but one example of the need for ever higher oscillator frequencies. Other examples include mm-waves for multi-Gb/s wireless communication, where there is much work at 60 GHz, and even demonstrations of 10 Gb/s transmission using a carrier frequency of 120 GHz [92]. Generation of microwave and mm-wave signals has

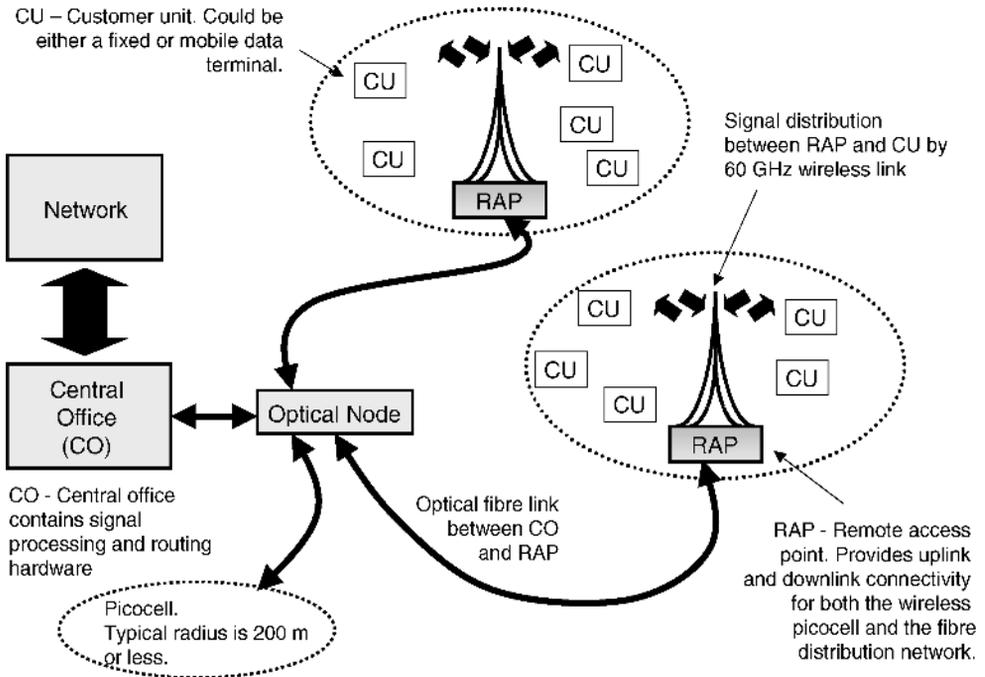


Figure 1.18 Architecture of a mm-wave fibre radio system

traditionally been the realm of electronic oscillators using III-V devices [93], although recent work has also proved the feasibility of using cheaper SiGe CMOS technology [94]. Nevertheless, as one goes beyond 100 GHz the power available from electronic oscillators declines. There is then a so-called ‘gap’ in the THz region before one reaches optical frequencies, where laser sources are available. The THz region itself is of growing importance in sensing and biomedical applications [95].

It is possible to use photonic techniques to generate mm-wave and THz signals, and one immediate advantage is that the signals can then be transported immediately over optical fibre. The availability of high-speed photodiodes and photomixers then ensures relatively efficient conversion into the wireless domain. The two obvious techniques for optical generation of microwaves are direct and external modulation as discussed above, but the former is limited to about 30 GHz while the latter can suffer from dispersion-induced fading at mm-wave frequencies. One can generate microwave and mm-wave frequencies by a number of other methods as discussed below:

- (a) *Heterodyning of two laser sources, in which the wavelength difference corresponds to the subsequent microwave signal’s frequency.* One advantage is that very high optical single-sideband frequencies can be generated. This is discussed in detail in Chapters 4, 5 and 10.
- (b) *Actively and passively mode locked lasers.* Of particular interest here is work at Drexel [96] on the use of microchip lasers. A microchip laser is a solid-state laser (based on erbium-doped lithium niobate for example) of short length onto which dielectric mirrors are deposited directly. It is a potentially low cost solution which is very suitable for mode locking at mm-wave frequencies. Performance-wise, the microchip laser is inherently more stable than a semiconductor laser, has higher output power and lower relative intensity noise.
- (c) *Optical phase locked loops (OPPLs) [97] and optical frequency comb generators (OFCGs) [98].* The OPLL architecture is similar to a conventional phase locked loop, but in this case a master and slave laser produce a heterodyne signal. After photodetection this is mixed with a mm-wave reference from an oscillator, and the resulting phase error signal is used to tune the slave laser so that the heterodyne signal frequency equals the reference frequency.

The OFCG is an amplified recirculating optical delay line into which a phase modulator is inserted. By applying microwave modulation to the modulator, and through the process of continued recirculation (and hence ‘remodulation’), an optical comb spectrum is generated in which the spacing between combs corresponds to the modulation frequency. One can then select two of the combs using injection-locked slave lasers and then subsequently photodetect the heterodyned signal. This technique can potentially produce frequencies well over 100 GHz.

- (d) *Optoelectronic oscillators (OEO) [99].* The basic configuration of an OEO (Figure 1.19) is based on the loop oscillator principle, in which the open loop gain must balance out losses. In this structure the oscillation frequency is inversely proportional to the fibre group delay. An OEO is a hybrid oscillator in the sense that it uses both microwave and photonic components, and the oscillation can be extracted either from the electronic part of the loop or the optical part. One of its perceived advantages is the potential to offer better phase noise performance than electronic oscillators at microwave frequencies [99] in addition to higher Q . A disadvantage of the scheme in Figure 1.19, however, is the thermal dependence of the fibre delay (although this does make it possible to use an OEO for sensing applications).

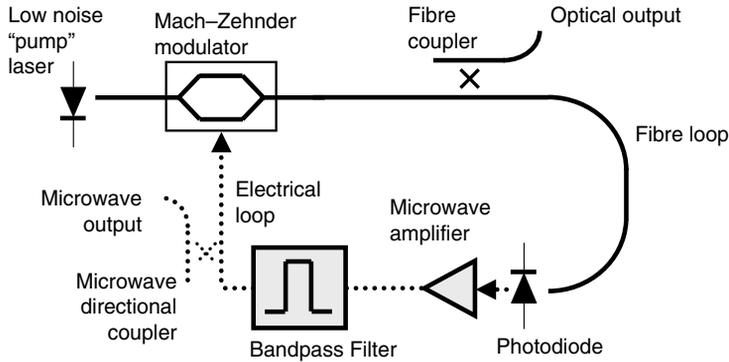


Figure 1.19 A single-loop optoelectronic oscillator

1.6.3 Signal Processing

As shown in Figure 1.4, optical fibre has a much lower loss than alternative technologies such as surface acoustic wave devices for a given delay. Put another way, this means that at a given microwave frequency an optical fibre can provide longer delays than competing media, which translates into a large time–bandwidth product. Single-mode fibre offers a time–bandwidth product in excess of 10^6 , thus making it suitable for the processing of wideband signals. An early application of microwave photonic signal processing was in optical fibre recirculating delay lines designed for the storage of microwave signals [100]. This was then followed in the early 1980s with implementations of microwave photonic filters at Stanford using delay line structures [101]. Since then the field has expanded significantly and a very large body of published work exists. Excellent review [102] and tutorial papers [103] provide a comprehensive discussion of much of this work.

An example of a very simple microwave photonic filter is shown in Figure 1.20. This architecture is an extension of the Mach–Zehnder interferometer, and can be shown to be

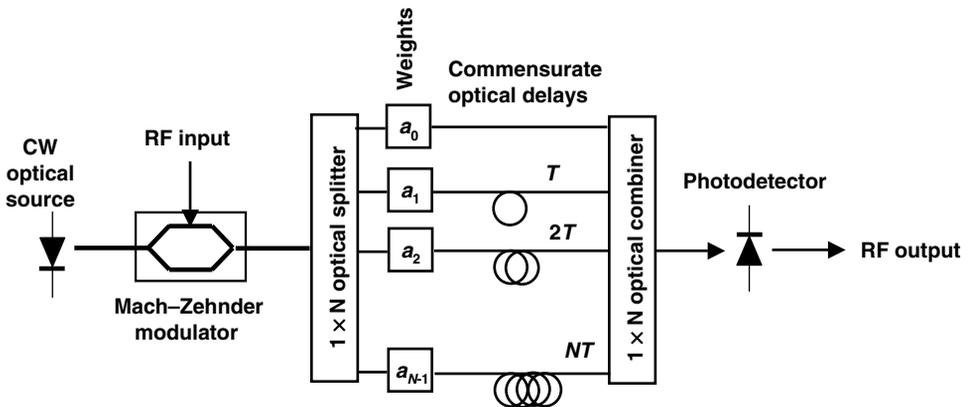


Figure 1.20 Example of a microwave photonic filter (for more details, see Figure 8.4 of Chapter 8)

functionally equivalent to a tapped delay line filter. Since the various fibre delays are commensurate, it is possible to use z -domain techniques from the field of digital filtering for analysis and synthesis purposes. (This is done for mathematical convenience, since microwave photonic filters are analogue.) Borrowing from digital filter terminology, the structure in Figure 1.20 is termed FIR (finite impulse response). It is also possible to have IIR (infinite impulse response) transfer functions by using recirculating loops.

Just as one might compare an analogue fibre link with a coaxial cable, one may compare a microwave photonic filter with a conventional microwave filter using lumped components, transmission lines or waveguides. The need for E/O and O/E conversion raises the question of whether the added complexity is worthwhile. However, given the increased interest in systems such as fibre radio, in which microwave signals are already being generated and transported optically, it seems reasonable to filter them in the optical domain as well. Moreover, as pointed out by Minasian [102], photonic signal processing offers numerous advantages, including high-speed, parallel processing and high sampling frequencies (in excess of 100 GHz as opposed to a few GHz for electronics). These advantages, coupled with advances in photonic technology such as fibre Bragg gratings (both uniform and chirped), optical amplifiers, high-speed modulators and detectors, WDM multiplexers and demultiplexers, and tuneable lasers, have created new opportunities not only for advanced microwave photonic filter structures but also other functions. Microwave photonics technology has been used to implement analogue to digital converters (ADC) [104], arbitrary waveform generators [105] and beamformers for phased array radars [106]. An example of a photonic ADC is shown in Figure 1.21; a good review of the field is given in [104].

1.6.4 Radio Over Fibre

Radio over fibre (RoF) is one of the major applications of microwave photonics and there is some significant commercial activity in this field. The main concept is shown in Figure 1.18 and

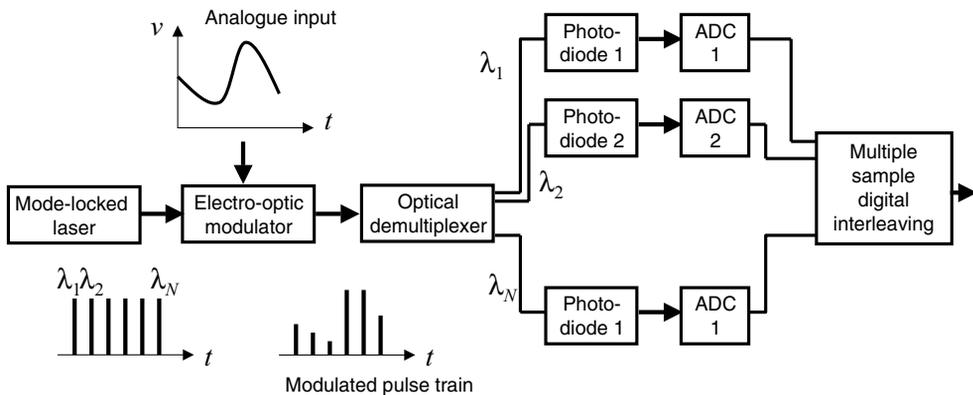


Figure 1.21 Example of a photonic analogue-to-digital converter. The analogue signal is sampled by a pulse train by using external modulation. The output of the external modulator is then demultiplexed according to wavelength prior to photodetection and electronic quantization. (There are examples of purely photonic ADCs, in which both sampling and quantization are performed in the photonic domain)

it involves the merging of wireless networks (indoor and also outdoor) with a fibre backbone (which is often WDM-based). Motivation for using RoF includes providing a solution to the ‘last mile’ problem and the improvement of wireless coverage (for example in buildings and ‘dark zones’ such as tunnels).

Indoor distributed antenna systems (DAS) currently have a large share of the RoF market [107]. They are designed to transport cellular and WLAN signals to remote antenna units distributed throughout a building, and the key driver here is to reduce costs. This is facilitated by the fact that the frequencies are low enough (in the range 800 MHz to 2.5 GHz) to allow the use of directly modulated laser diodes, even though device linearity is an issue. Since there is already a large amount of installed multimode fibre, significant efforts have been made to develop multimode RoF for DAS [108].

As the demand for higher data rates (for applications such as HDTV) continues to increase, more use will be made of mm-wave carrier frequencies. Of particular interest is the availability of several GHz of spectrum centred on 60 GHz, which will ease some of the spectrum congestion of cellular systems. The sizeable atmospheric losses at this frequency lead to relatively small cell sizes (known as picocells), thus allowing greater frequency reuse which enhances network capacity.

The small size of picocells means that a large number of remote antenna units must be produced, implying that their architecture must be suitably simple. In this manner the complexity moves to the central office, in which the functions of data modulation and multiplexing are housed. There are trade-offs between complexity of the picocells and the central office, leading to different schools of thought as to which is the best overall approach. These can be broadly defined as:

- (i) optical generation and transport of mm-wave signals at 60 GHz, and
- (ii) optical transport of data signals with remote upconversion to 60 GHz at the picocell site.

The former approach is known as RF over fibre. It results in simple picocell architectures, which at their bare minimum use electro-absorption transceivers [109] plus an antenna and associated circuits – this passive picocell approach removes the need for electronic amplification. It does, however, require use of the techniques described in Section 1.6.2 in order to generate the mm-wave carrier. The second approach is known as baseband over fibre and it removes the need for high-speed components, but in its place it requires local oscillators to be generated locally at each picocell unit. A third approach, known as IF over fibre is also possible, and this technique is illustrated in Figure 1.22 along with the other two signal transport approaches.

1.7 Conclusions

Microwave photonics is a field in which many advances have been made since the 1960s, and the high level of research activity continues unabated. In this introductory chapter we have sought to give a brief flavour of the topic from the perspective of devices and their various system applications. Later chapters will report on advances in some of these devices (e.g. direct modulation of lasers, photodiodes and THz generation with O/E and E/O devices) and will focus on how microwave photonic functionality can be used to implement microwave signal processing (e.g. microwave filters and analogue links) and to implement advanced communication systems (e.g. fibre radio).

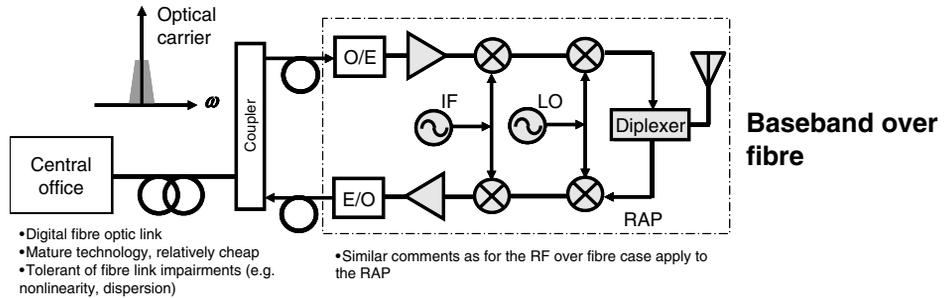
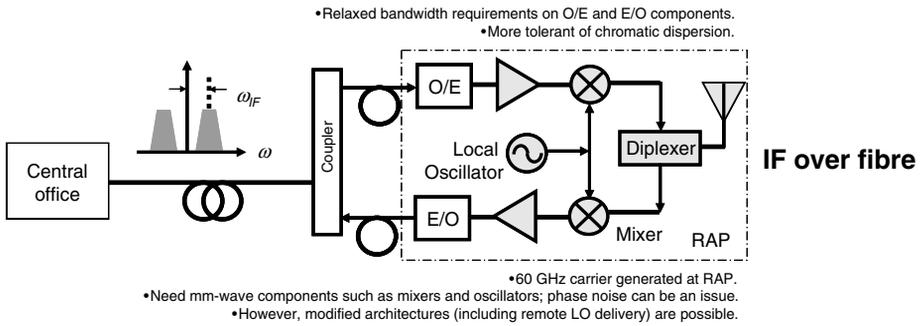
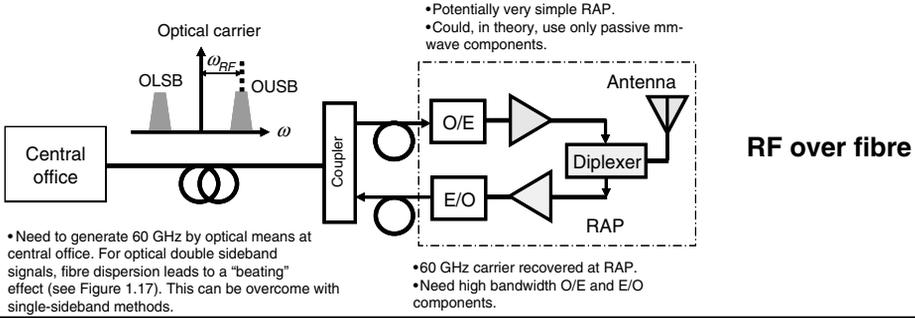


Figure 1.22 The three main classes of signal transport for radio over fibre compared and contrasted

It is highly likely that microwave photonics will continue to flourish as a research field, given that the demand for ever increasing bit rates in both wireless and optical communications shows no signs of stopping yet. There are also a number of growing applications in areas such as THz technology for sensing. To date, much of the progress in microwave photonics has been driven by impressive advances in optical fibre components. However, a number of key challenges remain (including the issue of producing low-cost components in high volumes) and there are also new opportunities on the horizon. These include:

- (i) the demonstration of high-speed modulators on silicon [110], which opens up a route to cheaper components that can be integrated with silicon drive electronics,

- (ii) ‘new physics’, such as the use of slow light to perform phase shifting for use in microwave filters [111], and
- (iii) the development of new structures such as micro-ring resonators that promise more compact optical filters designed with techniques that are well established in the area of microwave filters [112].

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