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Introduction

The purpose of this chapter is to give an overview of the field of optical communications, and modeling and simulation methods of optoelectronic integrated devices and circuits. The first section of the chapter describes why there are fundamental reasons why optics is attractive for use in communications; the most important components such as the optical transmitter, fiber, and receiver are introduced briefly. In the second section, the conventional computer-aided design (CAD) methods for optoelectronic devices and integrated circuits (ICs) are introduced.

1.1 Optical Communication System

The recent explosive growth of data traffic has stimulated the demand for high-capacity information networks. The data need to be transmitted from one place to another at high speed. There are essentially four possible methods to transmit these data [1, 2, 3]:

1. Free-space radio-frequency (RF) transmission
2. Free-space optical transmission
3. RF propagation over a fixed transmission line
4. Optical propagation over a fixed fiber-optic transmission line.

Free-space RF transmission is flexible and cheap, but it cannot support large (10 Gb/s) bandwidths and requires fairly large power to transmit over long distances. It is also relatively easy to intercept the transmitted signal, although with sufficient encryption it can be essentially impossible to decode. Free-space optical transmission is also quite flexible, but the signal quality and propagation distance are weather-dependent. Standard RF signal propagation over coaxial cable is simple to integrate with standard electronics and is ideal for relatively short distances and low data rates. Fiber-optic links

are being used increasingly to replace conventional guided-wave methods of conveying RF signals. Fiber-optical signal distribution is known to possess advantages over conventional signal distribution in cases where the signal must be transmitted over long distances, where signal security or low interference is desired, or where the size, weight, or cost of the distribution hardware is important. Fiber-optical transmission systems can replace normal coaxial or hollow waveguide signal distribution systems if the special characteristics of the electrooptical transducers can be tolerated. An additional advantage that makes millimeter-wave desirable for fiber radio systems is that these frequencies are highly attenuated by water molecules and oxygen in the atmosphere. This can be exploited to limit signal propagation to within the proximity of a picocell, as required for wireless secure communication and for frequency reuse.

Fiber-optic communication is 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 to carry information. Optical communication systems have been the mainstream information transmission systems in past decades and are still dominant today thanks to the invention and development of broadband semiconductor lasers, low-loss fibers, fast photodetectors, and other high-quality optoelectronic components. The fiber-optic link has many advantages, which include tremendous available bandwidth (~ 100 THz), very low transmission loss, immunity to electrical disturbance, and so on; all of this makes a fiber-optic link the preferred transmission solution in many applications.

Figure 1.1 shows a possible scheme for a 40 Gb/s optical transmission system. It requires several high-speed ICs having a bit rate of 40 Gb/s. In the transmitter, a

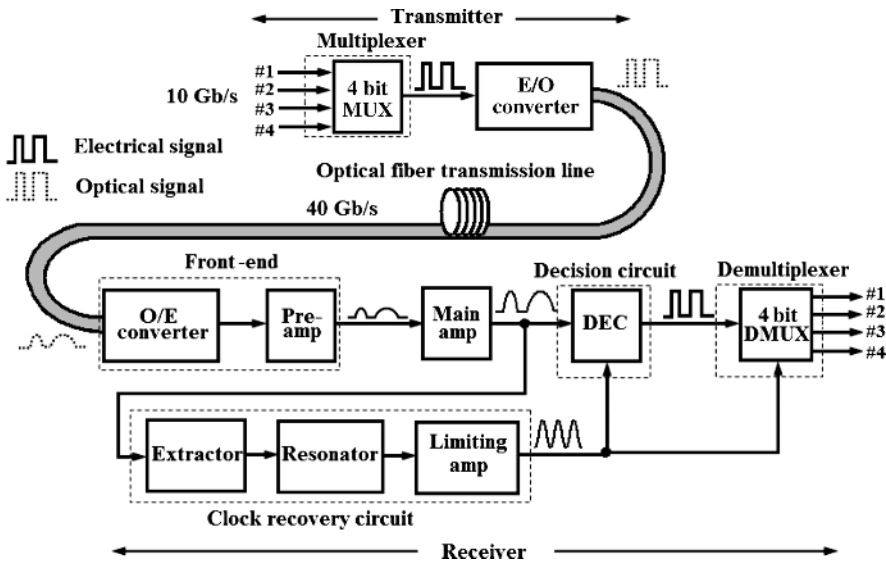


Figure 1.1 Schematic diagram of 40 Gb/s optical fiber transmission configuration.

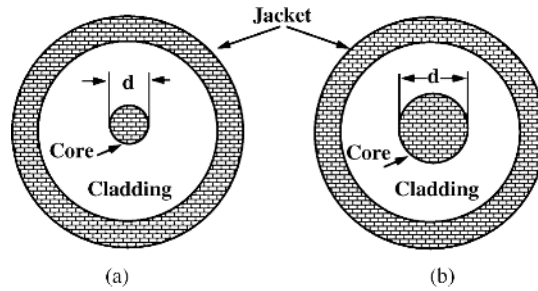


Figure 1.2 Cross-section of optical fiber: (a) single mode; and (b) multimode.

time-division multiplexer (MUX) combines several parallel data streams (four 10 Gb/s streams in Figure 1.1) into a single data stream with a high bit rate of 40 Gb/s. In the receiver, a demultiplexer (DMUX) splits the 40 Gb/s data stream back into the original four low bit rate streams. The MUX and DMUX are digital medium-scale ICs, which must achieve 40 Gb/s operation with suitably low power dissipation. In the receiver, the extremely small current signal generated by a photodiode is converted into a voltage signal and amplified by a low-noise preamplifier and succeeding main amplifiers having automatic gain control (AGC). The output voltage swing of the amplifier is kept constant, independent of the input signal level. Nevertheless, regeneration, performed by a decision circuit and a clock recovery circuit (composed of a differentiator, rectifier, microwave resonator, and limiting amplifier), is still needed to reduce the timing jitter produced by the cascaded amplifiers. The transmitter and receiver ICs, except for the clock recovery circuit, require broadband operation from near DC to the maximum bit rate with good eye openings.

Compared to the conventional communication system, the difference here is that the communication channel is an optical fiber cable. Figure 1.2 shows the cross-section of single-mode and multimode optical fibres. The cable consists of one or more glass fibers, which act as waveguides for the optical signal (light). In its simplest form an optical fiber consists of a cylindrical core of silica glass surrounded by a cladding whose refractive index is lower than that of the core. Fiber optic cable is similar to electrical cable in its construction, but provides special protection for the optical fiber within. For systems requiring transmission over distances of many kilometers, or where two or more fiber optic cables must be joined together, an optical splice is commonly used.

In multimode fiber, the light is guided by the almost perfect reflection at the interface between the core and cladding. Like multimode optical fibers, single-mode fibers do exhibit modal dispersion resulting from multiple spatial modes, but with narrower modal dispersion. Single-mode fibers are therefore better at retaining the fidelity of each light pulse over long distances than multimode fibers. For these reasons, single-mode fibers can have a higher bandwidth than multimode fibers. Multimode fiber has significantly higher loss (due to modal dispersion) than single-mode fiber and is therefore only used for short distance communications such as within a building or

on a corporate campus. All long-distance communications utilize single-mode fiber and laser light sources. In its simplest form an optical fiber consists of a cylindrical core of silica glass surrounded by a cladding whose refractive index is lower than that of the core.

Advantages of the optical fiber are as follows:

- Low attenuation, large bandwidth allowing long distance (>100 km) at high bit rates (>10 Gb/s)
- Small physical size
- Low physical mass, low material cost
- Cables can be made nonconducting, thus eliminating electromagnetic interference and shock hazards and providing electrical isolation
- Negligible crosstalk between fiber channels in the same cable
- High security, since tapping is very difficult
- Upgrade potential to higher bit rates is excellent.

Because of the rapid growth of capacity requirement on long-distance transmission, fiber-optic telecommunications is advancing into high data rate and wavelength division multiplexing (WDM) [4, 5]. WDM, by which multiple optical channels can be simultaneously transmitted at different wavelengths through a single optical fiber, thus multiply the capacity of the link (as shown in Figure 1.3). The advantages of WDM systems are: transmission capacity increase per fiber, system cost reduction, simultaneous transmission of different modulation-scheme signals, and service channel expandability after fiber installation. These are the reasons why WDM technology is expected to be widely applied to systems in various fields of communications. In WDM system design, performance of optical multi/demultiplexers (MUX, DEMUX) should be the primarily consideration, together with fibers, light sources, and photodetectors.

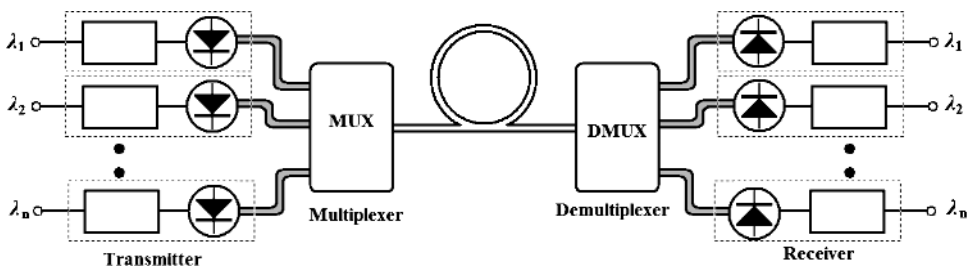


Figure 1.3 Fundamental configuration for WDM transmission.

Radio-frequency (RF) or microwave subcarrier multiplexing has recently emerged as a potentially important multiplexing technique for future high-capacity lightwave systems. Optical subcarrier multiplexing (SCM) is a method for multiplexing many

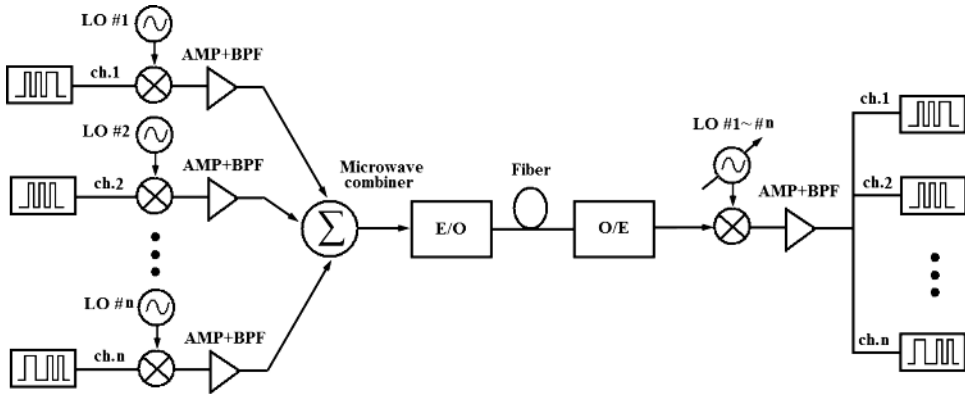


Figure 1.4 Basic SCM system configuration.

different fiber-optic-based communication links into a single uplink fiber [6]. SCM is a scheme where multiple signals are multiplexed in the radio-frequency (RF) domain and transmitted by a single wavelength. The basic configuration of an SCM system is shown in Figure 1.4. A number of baseband analog or digital signals are first frequency division multiplexed by using local oscillators (LOs) of different radio frequencies. The upconverted signals are then combined to drive a high-speed light source. The LO frequencies are the so-called subcarriers in contrast to the optical carrier frequencies. A significant advantage of SCM is that microwave devices are more mature than optical devices; the stability of a microwave oscillator and the frequency selectivity of a microwave filter are much better than their optical counterparts. In addition, the low phase noise of RF oscillators makes coherent detection in the RF domain easier than optical coherent detection, and advanced modulation formats can be applied easily.

1.2 Optoelectronic Integrated Circuit Computer-Aided Design

Intense research to develop and expand the capabilities of fiber-optic technology is under way. The outstanding progress made in optical fiber transmission systems has been largely dependent on newly developed optical and electronic semiconductor devices. To realize high-bit-rate systems, high-speed transmitter and receiver circuits are in great demand, and the development of monolithic ICs, which have higher performances and multiple functions, is indispensable. The gigabit optical transmission systems must not only be high speed but also compact, cost effective, and highly reliable, and must minimize both power consumption and temperature rise, which increase with higher transmission speeds. One of the most effective ways to achieve such a system is with gigabit IC technology. Driver circuits and preamplifiers, which are directly connected to optical devices, are among the key components.

The proliferation of optical and fiber-optic communications has created a need for efficient and accurate CAD tools for the design of optoelectronic integrated circuits and systems. In the electronic world, highly advanced CAD tools exist for the design, analysis, and simulation of nearly every aspect of integration, ranging from process to device to circuit to system. The application of modern CAD tools offers an improved approach. As the sophistication and accuracy of these tools improve, significant reductions in design cycle time can be realized. The goal is to develop CAD tools with sufficient accuracy to achieve first pass design. The CAD tools need to be improved until the simulated and measured RF performance of the component being designed are in good agreement. This will permit the design to be completed, simulated, and fully tested by an engineer working at a computer workstation before fabrication is implemented. In order to achieve this goal, improved accuracy CAD tools are required.

The state of the CAD methods for active optoelectronic circuits rely heavily on models of real devices. There are two kinds of commercial optoelectronic device and integrated circuit CAD software: physical-based and equivalent-circuit-based CAD software. The physical-based CAD software, as a starting point of analysis, considers fundamental equations of transport in semiconductors. The equivalent-circuit-based CAD software addresses the issue of what needs to be known about the device in addition to its equivalent circuit to predict the performance. The model permits the RF performance of a device or integrated circuit to be determined as a function of process and device design information and/or bias and RF operating conditions. The equivalent circuit device models must be based upon accurate parameter extraction from experimental data. The model permits the RF performance of a device or integrated circuit to be determined as a function of process and device design information and/or bias and RF operating conditions. Figure 1.5 shows the flowchart for an ideal

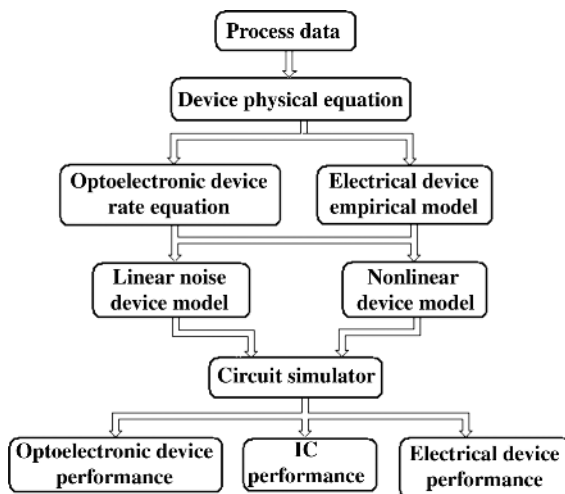


Figure 1.5 A flowchart for ideal microwave and RF circuit simulator.

optoelectronic circuit simulator. Such an integrated simulator allows both the active devices and passive elements to be optimized, based upon the parameters accessible in the fabrication process.

1.3 Organization of This Book

We will spend the rest of this book trying to convey the basic operation mechanism of the key components of high-speed optical communication. The focus will be on how to build the linear, nonlinear, and noise models for optoelectronic devices (including lasers and photodiodes) using physical rate equations and how to design optimum laser/modulator driver and receiver front-end circuits using microwave matching techniques.

In Chapter 2, the physical structure and basic concept of the most commonly used semiconductor laser diodes have been discussed. Based on the rate equations in the active region, the small signal modulation, large signal modulation, and noise performance of laser diode are formulated, and the corresponding measurement techniques are introduced.

Chapter 3 presents the rate-equation-based modeling and parameter extraction techniques for semiconductor lasers. By using the microwave active device modeling concept, the rate equation model parameters can be determined. The standard double heterojunction semiconductor lasers and single quantum-well lasers are used as examples. The model parameter extraction techniques for the extrinsic elements, intrinsic elements, and rate equations model parameters are described in more detail.

In Chapter 4, we introduce the physical structure and operation concept of the commonly used photodiodes (such as PIN PD, APD, and MSM PD). The small-signal modeling and parameter extraction method are described.

The high-speed electrical devices such as field effect transistor (FET), heterojunction bipolar transistor (HBT), and metal oxide semiconductor FET (MOSFET) are very attractive for a high-speed optoelectronic integrated circuit. In Chapter 5, the basic physical structures and operation concepts of various semiconductor devices are introduced, and the corresponding small-signal, large-signal, and noise modeling and parameter extraction methods are described briefly.

The laser/modulator driver and receiver front-end are two key components of high-speed optical communication systems. Chapters 6 and 7 deal with the optimum design of 10 Gb/s to 40 Gb/s high-speed laser/modulator driver and receiver front-end integrated circuits based on different semiconductor technologies. The passive peaking techniques, which include inductance and capacitance techniques for extending bandwidth and minimizing the noise performance for the driver and receiver, are described in more detail.

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