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Kai Chang, Series Editor

Fundamentals of Microwave Photonics

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For Cindy, Amanda and Vicki

CONTENTS

PREFACE

This volume provides what we believe to be a thorough treatment of the microwave photonics field, sometimes referred to as RF or analog photonics. The intended audience ranges from an advanced undergraduate student in engineering or physics to experts in the field. The treatment is fundamental in nature and could be used in an advanced undergraduate or graduate-level course to introduce students to microwave photonics. Although a problem set is not included, there are instances throughout where an inventive instructor could devise assignments. It is our hope that seasoned veterans of the field will find this book most useful for a variety of reasons. We have tried to provide as much of the basic underlying physics as is possible in a work of this size. Sometimes, this information can be lost in a field as applied as microwave photonics. Plots that give bounds on performance for a variety of scenarios abound. A thorough list of references is provided for each chapter, including original sources where applicable. Design equations in easy-to-use forms are provided throughout and are intended for quick reference. Indeed, we plan to keep this volume readily accessible in the laboratory, in the field, or during design meetings.

We intended for this book to flow continuously from the first to the last page and believe we have succeeded in this endeavor. Beginners in the field are encouraged to read continuously, as the later chapters build on foundations laid in the earlier ones. Those more experienced in the field should find that navigation of the individual chapters is readily achievable. Chapter 1 gives an introduction to microwave photonics and stands on its own, pointing to later chapters where more detail is provided. Chapter 2 describes the radio-frequency metrics that are most important to quantifying performance of microwave photonics systems and is largely divorced from optics. Chapters 3 through 5 provide fundamental treatments of noise, distortion, propagation, and fiber nonlinearities as they pertain to microwave photonics. These three chapters do not concentrate on any single modulation mechanism but rather are intended to provide a generalized treatment. Specific modulation and corresponding demodulation techniques are covered in Chapters 6 through 8, using the material in the previous four chapters. In Chapter 6, intensity modulation with direct detection employing an external Mach–Zehnder modulator is detailed. This technique is arguably the most prevalent today and therefore receives the most thorough treatment. Phase modulation is covered in Chapter 7 but with slightly less detail. Complete but relatively brief analyses of numerous other modulation formats are conducted in Chapter 8. Chapter 9 is concentrated on high power photodetectors. System and subsystem applications are covered in Chapter 10, which also describes some of the present trends in the field.

We ourselves acquired a more complete knowledge of many topics while writing this book and the work inspired many new concepts. We sincerely hope the same is true for all who pick up this volume.

VINCENT URICK
JASON MCKINNEY
KEITH WILLIAMS
Washington, DC, April 2014

ACKNOWLEDGMENTS

This book was written as a private work, and as such, the opinions expressed in this book are those of the authors and do not reflect the official position of the US Naval Research Laboratory (NRL), the US Navy, or the US Government. That being said, this work would not have been possible without the support of NRL throughout our careers. The work environment provided at NRL has made it possible to make steady progress in developing a thorough understanding, both experimental and theoretical, of microwave photonics technology. This would not have happened without the support of the management at NRL, specifically the Superintendents and Branch Heads who were instrumental in supporting our ability to make progress in this important technology area. Those individuals include Dr. Francis Klemm, Dr. Thomas Giallorenzi, Dr. John Montgomery, Dr. Joseph Weller, Dr. Ronald Esman, Mr. Michael Monsma, and Dr. Don Northam. We would also like to acknowledge those staff at NRL, both past and present, who have contributed to the development of microwave photonics.

We are indebted to the countless colleagues and collaborators that we have had the pleasure to work with over the years. The citations in the text name many of those who have inspired us but some are deserving of special mention. Firstly, Dr. Frank Bucholtz at NRL has provided significant insight into the analysis and understanding of analog optical links. His work is cited where applicable but his contributions to our progress go well beyond those instances. Professor Nicholas Frigo of the US Naval Academy Physics Department assisted with the development of sections pertaining to polarization effects. Mr. Carl Villarruel, NRL (retired), has spent countless hours discussing the technical fine points of microwave photonics with us, particularly in areas concerning optical fiber effects. Dr. Preetpaul Devgan of the US Air Force Research Laboratory stimulated important concepts pertaining to modulation formats. Dr. Andrew Kowalevicz from Raytheon Company inspired useful viewpoints on optical fields in various media. Dr. Marcel Pruessner at the NRL provided valuable feedback on silicon integration for microwave photonics applications. Dr. Olukayode Okusaga, US Army Research Laboratory, gave insight into the subtitles of optoelectronic oscillators. Mr. Bill Jacobs, US Space and Naval Warfare Systems Command, provided alternative views on applications of microwave photonics and also assisted with professional responsibilities while this book was being written. We acknowledge Dr. Thomas Clark Jr. at Johns Hopkins Applied Physics Laboratory for discussing aspects of multioctave millimeter-wave photonics and signal processing. Finally, we wish to thank all the ambitious students we have instructed and those we have mentored for allowing us to pass on what we have learned. It is in those instances when one realizes that you don’t truly understand something until you can teach it to someone else, a concept that was reinforced tenfold while writing this book.

Beyond the mainly professional acknowledgements mentioned previously, there are numerous individuals who have influenced us in profound ways. This work would have never come to be if it weren’t for our parents and families. Our wives and children were supportive during the writing process, making numerous concessions along the way. We are forever grateful to our parents, Vincent Urick Sr., Susanne Urick, Dwight McKinney, Deborah McKinney, and Gertrude Williams. They nurtured intellectual curiosity in us and instilled a work ethic that was required to complete this book. Paul Urick, an old-time farmer from Pennsylvania, and Norman Zlotorzynski, a kind man who survived Omaha Beach in 1944, always provided inspiration when it was needed most. They both passed away while this book was being written and would like to have seen the completed work.

CHAPTER 1

INTRODUCTION

Microwave photonics is a multidisciplinary field that encompasses optical, microwave, and electrical engineering. The microwave photonics field must therefore span frequencies of below 1 kHz in the radio-frequency (RF) domain to frequencies of hundreds of terahertz associated with the optical domain. The field originated from the need to solve increasingly complex engineering problems when radio engineers ventured outside their discipline to the optical domain in search of new capabilities. Generally, the field is applied in nature stemming from its roots and driven by present-day system needs. However, many basic research areas are associated with the underlying component technologies.

Although the field of microwave photonics was not formalized internationally until the late 1980s and the early 1990s (Berceli and Herczfeld, 2010), its history spans more than a few decades. The use of RF for telegraph communications in the early to mid-1800s gave birth to the need for radio engineers. However, it was not until the expanded development of radar during World War II (Page 1962) to search for aircraft electronically did the need for those with analog or radio engineering skills increase dramatically. Nearly as quickly as

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radar was established as a useful tool to aid in detection, radar countermeasures were developed to confuse and deny the radar operators effective use of their new tools. Countermeasures necessitate radar redesign in order to render countermeasures ineffective. This iterative countermeasure/counter-countermeasure battle continues today and will so long into the future as the radar designer is constantly trying to "see and not be seen" (Fuller 1990). The use of higher frequencies and the desire to delay those frequencies created a need for low loss delay lines. The early promise of microwave photonics technologies for low loss long delay lines is closely linked to this radar and electronic countermeasure battle.

Today's society makes abundant use of the electromagnetic spectrum for communication. Radio and television broadcasts, cell phones, satellite communications, push-to-talk radios, and many other techniques have been developed to facilitate communication between two or more parties. These systems make use of RF signal transmission and processing within the devices. Due to the expansion of microelectronic circuits and their size/power/speed advantages, many of these systems have moved from strictly analog systems to mixed-signal implementations. In these systems, analog signals are digitized, processed, and/or transported in digital form before being converted back to continuous waveforms for use in the analog world. Although modern RF systems increasingly use digital signal processing (DSP), analog fiber optic links offer the radio engineer significant and useful tools in the design of these systems. The ability to process a signal in the analog domain can simplify overall system design, especially in wide bandwidth systems, where bandwidth demands are difficult to achieve with DSP. However, the analog system engineer should use the best analog tools along with the features that DSP can provide to make the most efficient and powerful system possible.

In its most basic form, an analog photonic link is a delay line containing an electrical-to-optical (E/O) converter to transform the RF signal into the optical domain, an optical transmission medium, and an optical-to-electrical (O/E) converter. Figure 1.1 illustrates a functional block diagram for a multichannel fiber optic link. One or more RF inputs are converted into the optical domain by E/O converters. Once the RF signal has been transformed into the optical domain, it can be delayed in time with optical fiber, processed, and delivered to one or more O/E converters where the optical signals are demodulated back into electrical RF signals. The processing elements can take many forms, including switching, routing, filtering, frequency translation, and

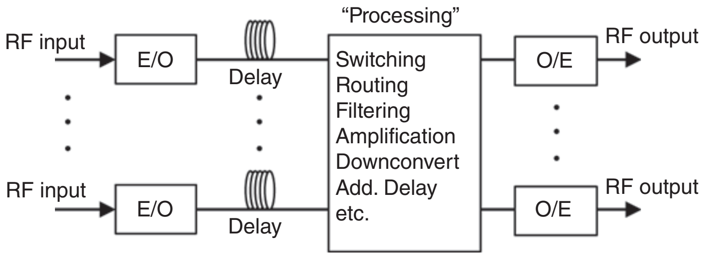

Figure 1.1. Basic block diagram of an array of fiber optic links.

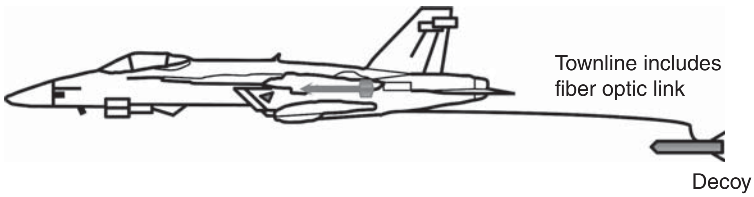

Figure 1.2. A depiction of an RF towed decoy from an F/A 18.

amplification, to name a few. The performance of various forms of such analog photonic links will be treated throughout the middle chapters.

Fiber optic links have proved to be advantageous over their electronic (coaxial cable) counterparts for a number of applications. One of the early military applications was the use of a fiber optic link in an airborne towed decoy as shown in Figure 1.2, the ALE-55. The concept of a towed RF transmitter from an aircraft to distract an RF-guided missile away from its intended target has existed since, at least, the 1960s (Norman and Meullen, 1964), with fiber optic versions appearing later (Toman 1989). In early designs, a receiving antenna on the decoy detected a threat, amplified, and then re-transmitted a higher power return signal. However, due to the size limitations necessitated by aerodynamics of the decoy, only a limited amount of signal processing can be performed on the decoy itself. The use of a fiber optic cable to connect the airplane and the decoy makes it possible to use sophisticated signal processors onboard the aircraft, remoting processed signals to the decoy where amplification and transmission occur. This allows the decoy to be used in a multiphase approach for defeating a threat missile including suppressing the radar's ability to track the aircraft, deceiving the radar with jamming techniques, and seducing the missile away from the aircraft by presenting a more attractive target. Fiber optics minimizes the size of the decoy and reduces the tension on the decoy towline, allowing it to be useful on a wider variety of aircraft.

One of the first widespread commercial uses of analog fiber optic links was in hybrid fiber-coaxial (HFC) systems for cable television signal distribution (Chiddix et al. 1990). HFC solutions offered cable system operators the ability to increase the number and quality of video signals delivered to the home and to provide upstream broadband data services at low cost with high reliability. HFC systems transformed the role of the cable industry from being strictly a provider of video to a viable competitor in the local access market, traditionally served by the telephone system. Combined with the expansion of the Internet, this has helped to shape the competitive broadband information infrastructure as it exists today. By the mid-1990s, HFC systems were capable of delivering over 100 channels of amplitude-modulated vestigial-sideband (AM-VSB) video distances of over 20 km with a variety of optical link designs. The key to this success was the ability to deliver video signals optically having high carrier-to-noise ratios (CNR) and low composite second-order (CSO) and composite triple-beat (CTB) distortion levels. Significant early work on improving the linearity of analog optical links was performed for this application, including work on linearizing external modulation (Nazarathy et al. 1993) and study of crosstalk due to optical fiber nonlinearities (Phillips and Ott 1999). A significant portion of this book is devoted to sources of nonlinearity in analog optical links. Almost as quickly as HFC changed the cable and telephone industry, conversion from AM-VSB video distribution to compressed digital video (CDV) began. Although the conversion was slow due to the cost of replacing an entrenched and expensive infrastructure, CDV has now displaced much of the AM-VSB video distribution technologies. As with the legacy AM-VSB signals, fiber optic links remain the transmission medium of choice for such modern telecommunication systems.

In radio astronomy, large antennas are used to detect RF emissions from space. Microwave engineering plays a crucial role in radio astronomy, with analog fiber optic links being used in modern systems (Webber and Pospieszalski 2002). The Greenbank Telescope (GBT), located in West Virginia and operating from 0.1 to 115 GHz, is the world's largest fully steerable single antenna (Lockman 1998, Prestage et al. 2009). The 100-m-diameter parabolic antenna is used to enhance scientific understanding in areas such as the detection of gravitational waves (through precision pulsar timing); the formation of stars, galaxies, and galaxy clusters; and the composition of planets. The antenna is used for the detection of atomic and molecular emission lines spanning from high red-shift situations (emissions near black holes) to those where the measurement of weak, spatially extended spectral lines can be used to detect new organic molecules in space. The GBT uses an analog fiber optic link for remoting signals to a processing laboratory (White 2000). For higher spatial resolution, smaller dish antennas can be used in a phased-array configuration to take advantage of long baselines to measure small phase changes. Such an array was inaugurated in 2013 in the mountains of Chile (Testi and Walsh 2013), a portion of which is shown in Figure 1.3. Fiber optic links to remote the millimeter wave signals have shown potential utility in large radio astronomy antenna arrays (Payne and Shillue 2002). Because the RF signals originate at astronomical distances and are thus very low power, large antenna systems with very low noise figures are assembled and operated as large phased arrays. Such systems take advantage of the array gain from a large effective aperture and the phase sensitivity of a long baseline. In some systems, as many as 64 12-m dish antennas operating over a 16-km baseline must have their RF signals coherently summed at a central location. Since the frequencies of interest may reach hundreds of gigahertz, relative path differences must be precisely accounted for. This is very challenging, even for fiber optics (Thacker and Shillue 2011), as temperature variations, polarization drift, and chromatic dispersion all lead to length errors requiring active compensation. Additional details on the fiber links for the GBT and ALMA are provided in Chapter 10.

Figure 1.3. The Atacama large millimeter/sub-millimeter array (ALMA) interferometer in Chile. (*Credit:* ALMA (ESO-NAOJ-NRAO), J. Guarda.)

The aforementioned applications are just a few of the many within RF, microwave, or millimeter-wave systems where fiber optic links have proven useful. Microwave photonics provides utility in areas spanning the military, industrial, and academic sectors. Other applications include radio-over-fiber for wireless communications, delivering power to and from antenna feeds for antenna and array calibration, signal routing and true time delay beamforming in arrays, optical signal processing, filtering, waveform synthesis, optoelectronic oscillators for the precision generation of RF signals, optical clocks for precision timing, and RF downconverters and upconverters. The underlying technology and components contained within analog optical links are the subjects of this book, including more detail on applications of the technology in Chapter 10.

1.1 ENABLING TECHNOLOGICAL ADVANCES AND BENEFITS OF FIBER OPTIC LINKS

The frequency range of interest to the field of microwave photonics depends to a large degree on Mother Nature. Figure 1.4 (Liebe 1983) shows the atmospheric attenuation of RF radiation at sea level under different atmospheric conditions. As can be seen, there are

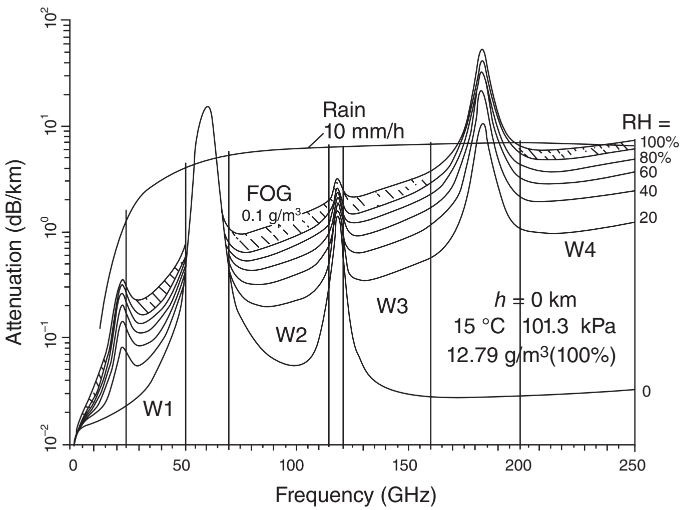

Figure 1.4. Specific atmospheric attenuation at sea level for various levels of relative humidity (RH), including fog and rain. Transmission windows are designated W1–W4 (Liebe 1983).

strong absorption bands near 23, 60, 119, and 182 GHz. Between these frequencies are transmission “windows” with comparatively less loss. Systems using frequencies below 20 GHz have proliferated for ground-based or sea-level applications, with a few systems operating in the second and third windows, centered around 35 and 94 GHz, respectively. Inspection of Figure 1.4 implies that these systems are functioning with an atmospheric attenuation of 0.3 dB/km or less at sea level. At altitudes above 9.2 km, the attenuation decreases in these atmospheric transmission windows to below 0.05 dB/km at frequencies up to 300 GHz (Wiltse 1997). Given that 0.3 dB/km is an acceptable level of attenuation at sea level, it then becomes plausible to consider the use of frequencies up to 300 GHz at high altitudes such as in air-to-air applications. In terms of fractional bandwidth, 300 GHz is only 0.16% of the bandwidth of an optical carrier at 1550 nm (193 THz). This small fractional bandwidth allows many applications to be realized in photonics, including RF signal multiplexing. In addition, many photonic device technologies have been shown to be feasible in the 100–300 GHz range, making the technology suitable throughout this entire frequency range (see Section 10.5). The field of microwave photonics evolved largely due to such application needs. However, before the technology could prosper, several significant breakthroughs were needed, including low loss optical fibers and efficient high bandwidth transducers (E/O and O/E).

Figure 1.5 shows a typical cross-section and index profile for a step index optical fiber. A high index glass core having index of refraction n_1 and diameter d_1 is surrounded by a slightly lower index glass cladding

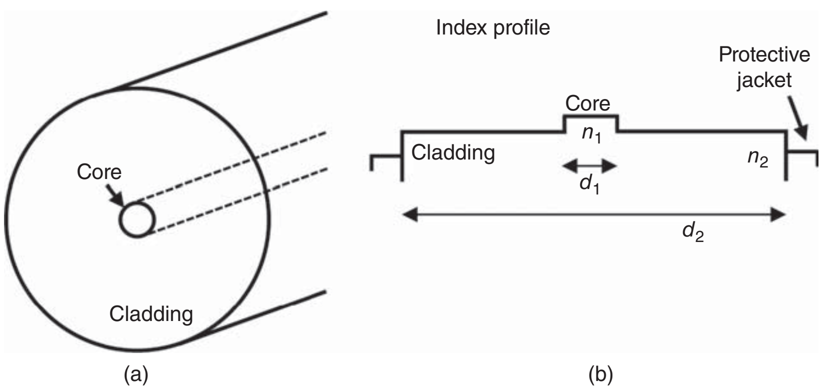

Figure 1.5. (a) Depiction of single mode fiber core and cladding regions with index profile (b) for a step index waveguide design.

having index n_2 and diameter d_2. The cladding is sufficiently thick such that the evanescent electric field of the propagating mode(s) exponentially decays in this region. The cladding glass is usually coated with a lower index polymer for environmental protection. Typical core and cladding diameters are from 8 to 50 μm and from 60 to 125 μm, respectively. The core–cladding index difference and the diameter of the core determine how many propagating modes the fiber waveguide can support for a particular wavelength.

Maxwell's equations describe the propagation of waves within the dielectric waveguide of an optical fiber. From a solution to the wave equations, a normalized frequency or V-number for the fiber can be defined as

$$V = \frac{\pi d_1}{\lambda}\sqrt{(n_1^2 - n_2^2)}, \tag{1.1}$$

where λ is the wavelength. For typical optical fibers, the normalized index difference, $\Delta = (n_1 - n_2)/n_1$, is usually $\ll 1$, and Equation (1.1) reduces to

$$V = \frac{\pi d_1}{\lambda} n_1 \sqrt{2\Delta} = \frac{\pi d_1}{\lambda}\mathrm{NA}, \tag{1.2}$$

where NA is the numerical aperture of the fiber. In ray optics, NA = $n_0 \sin(\theta)$, where θ is the acceptance half-angle, and n_0 is the index of the material in front of the fiber interface ($n_0 = 1$ for air). The NA is a measure of the light-gathering capacity of a fiber whereby light impinging on the fiber at an angle greater than θ relative to the propagation axis does not excite a guided mode. One can show that for all values of V up to the first zero of the Bessel function J_0 such that $J_0(V) = 0$ (see Appendix VI) that the waveguide can only support the lowest order hybrid mode, HE11 (Ramo et al. 1994). Thus, for $V < 2.405$, the waveguide is single mode. When V exceeds 2.405, the waveguide supports higher order modes, and for large V, the number of supported modes can be estimated to be $V^2/2$. A typical single mode fiber at 1550 nm has a core diameter of 10 μm, allowing for an index difference of 0.006 or less to remain single mode. Such small index differences are possible by adding dopant materials such as GeO_2, P_2O_5, or B_2O_3 to pure fused silica glass (SiO_2).

Multimode fibers with larger cores were fabricated earlier than single-mode fiber and typically achieved lower loss due to the higher tolerances to waveguide dimensional imperfections. However, RF photonic links at high frequencies use single-mode fibers almost exclusively to avoid power fading experienced in multimode fibers due to

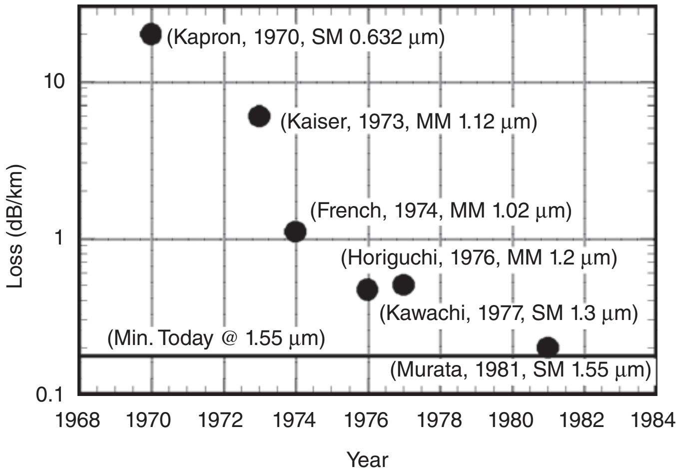

Figure 1.6. Reported losses in optical fiber over time for single-mode (SM) and multimode (MM) fibers at various wavelengths (French et al., 1974;Horiguchi, 1976; Kaiser, 1973; Kapron, 1970; Kawachi, 1977; and Murata and Inagaki, 1981).

modal dispersion. Figure 1.6 shows the progress over time of the optical losses of multimode and single-mode fibers in terms of propagation loss. Fundamentally, the loss is limited by Rayleigh scattering in the fiber, which amounts to a loss of 0.175 dB/km at 1550 nm. As can be seen from Figure 1.6, fiber loss decreased to below 1 dB/km by 1974 and was within 10% of the Rayleigh scattering limit by 1981. It will be demonstrated in later chapters that for many link modulation formats, the RF loss in a microwave photonic link is twice that (in decibels) of the optical loss. Therefore, by 1981, RF delay line propagation loss would have been as low as 0.4 dB/km at 1550-nm wavelength. Since the wavelength dependence of the loss is minimal over a few nanometers bandwidth (hundreds of gigahertz bandwidth at 1550 nm), the RF propagation loss is practically frequency independent.

Low optical fiber loss offered the promise of substantial performance advantages in RF delay lines if the subsequent transducers from E/O and O/E could be developed in the frequency ranges of interest. Initially, the most important frequency range of interest was the region below the first atmospheric absorption feature including frequencies up to 20 GHz (Figure 1.4) where a substantial number of deployed RF systems existed. On the E/O side, the semiconductor laser was an early choice due to the sub-ns photon lifetimes in GaAs (wavelengths up to 860 nm) and InGaAsP (wavelengths up to 1600 nm). Direct modulation of the pump current for these lasers provides a straightforward E/O mechanism. Demonstrations up to 10 GHz modulation bandwidth were prevalent by the mid-1980s (Su and Lanzisera 1986). The first demonstration of a semiconductor laser to surpass 20 GHz bandwidth was at 1.3 μm, using a buried heterostructure in a bulk material (Olshansky et al. 1987). Research continued in this area to improve differential efficiency (leading to higher E/O conversion efficiency) and to increase bandwidth. It was widely expected that multiple quantum well laser designs would help to improve differential efficiency because of their carrier confinement properties and low carrier densities required for inversion (Okamoto 1987). However, it was not until the high speed carrier transport into and out of the quantum wells was studied and understood (Nagarajan et al. 1992) that the bandwidths of quantum well lasers exceeded those made without quantum confinement. Distributed feedback (DFB) laser designs quickly followed, allowing for single-longitudinal-mode operation. While 20 GHz bandwidth lasers satisfy a large number of RF system applications, semiconductor laser intensity noise near the modulation bandwidth limit peaks, leading to lower signal-to-noise ratios (SNR). This intensity noise (or relative intensity noise—RIN) peak can be mitigated by increasing the modulation bandwidth; DFB lasers achieving 25 GHz bandwidth at 1550 nm (Morton et al. 1992) and over 40 GHz bandwidth (Weisser et al. 1996) have been reported.

On the back end of the link, an O/E converter is required to convert RF modulation impressed on the optical carrier back into an RF signal. The most significant device for this is the p–n junction photodiode incorporating a depleted intrinsic region to reduce capacitance, referred to as a p–i–n photodiode. Early work on high speed photodiodes yielded substantially higher bandwidths than their high speed laser counterparts (Bowers et al. 1985), and photodiodes were generally not the bandwidth-limiting device within the first links. There are design trades for these photodiodes when implemented in bulk surface-illuminated structures (Bowers and Burrus 1987); increasing the depletion region thickness lowers capacitance (increases bandwidth) and improves absorption efficiency but causes carrier transit times to increase (decreasing bandwidth). This tradeoff can be avoided by using waveguide or distributed traveling wave designs that improve both efficiency and bandwidth at the expense of device and packaging complexity.

In addition to low propagation loss, the information bandwidth available and the frequency independence of the loss in fiber are just as

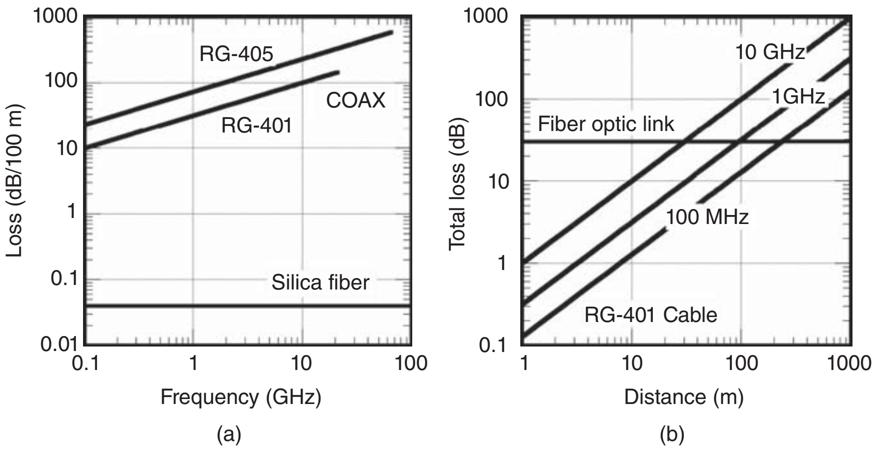

Figure 1.7. Loss as a function of (a) frequency including only propagation loss in the cable for RG-401, RG-405 and silica fiber and (b) propagation distance for RG-401 at three frequencies. In (b), the fiber optic loss includes a 30 dB fixed loss due to E/O and O/E conversion.

important for RF fiber optic links. This is in stark contrast to propagation loss in an RF coaxial cable that tends to have a square root dependency with frequency. As an example, consider Figure 1.7(a) where the propagation losses in two coaxial cables, RG-401 and RG-405, are plotted versus frequency along with the propagation losses of optical fiber. In general, larger diameter cables such as RG-401 tend to have lower loss but also have a lower cutoff frequency for the waveguide to remain single mode. Note how the coaxial cable loss increases by one decade for every two decades in frequency, characteristic of losses that have a square root dependency with frequency. Note also that the propagation losses in coaxial cable are two or three orders of magnitude higher than those of optical fiber. This reason by itself has led the push for the further development of microwave photonics technology through the present day.

When E/O and O/E transducer losses are included with the propagation loss in the comparison between coaxial cable and fiber, the differences are not quite as pronounced as Figure 1.7(a) might suggest. The total loss in a fiber optic link and the propagation loss in RG-401 at three different frequencies are plotted in Figure 1.7(b) as a function of distance. Included in the fiber optic link loss is a 30-dB transducer loss due to the E/O and O/E conversion losses. Because of the exceptionally low propagation loss, there will always be a length for which the fiber optic link will outperform coaxial cable from a loss perspective. This crossover distance tends to be higher at lower frequencies, but distances between tens of meters to a few hundred meters are typical. If loss were the only factor, long distance links would always use fiber; however, factors other than loss also contribute to the decision matrix. Cost, noise performance, phase stability, size, immunity to electromagnetic interference (EMI), and other factors can all play a role. These additional considerations can tip the scales toward fiber optics even for very short links. For example, the relative phase change after propagating an optical fiber is compared to that for a coaxial cable using normalized units of parts per million (ppm) in Figure 1.8. Coaxial cable comprises many different materials including solid and stranded metals, different metal types, and various dielectric materials, all having their own coefficients of thermal expansion. This causes the group velocity of coaxial cable to be a complicated function of temperature. In contrast, optical fiber is primarily made from fused silica. Changes in the propagation delays with temperature are due to the temperature dependencies in both the physical waveguide length and in the index of refraction (also see Section 5.3). Uncoated fiber, if it is not mechanically attached to another material with a large thermal expansion coefficient, has an 8 ppm change in delay per unit length per degree of temperature (Hartog et al. 1979). This includes both the material and waveguide dimensional temperature dependencies. The length fluctuation is both very low and very predictable over a wide temperature range, so long as the temperature dependencies associated with fiber coating or cabling

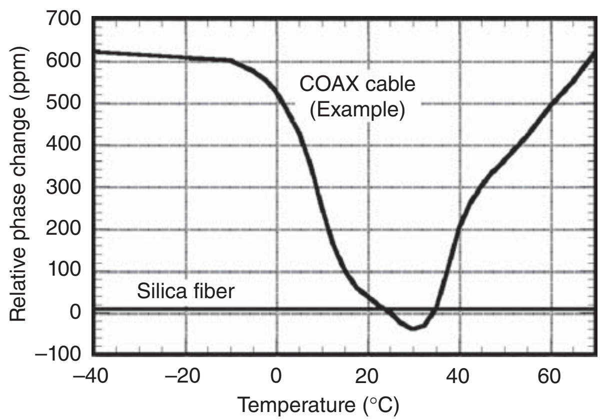

Figure 1.8. Relative phase change versus temperature for a coaxial cable and for optical fiber.

techniques are minimized. This property can be very advantageous in systems where phase stability or phase predictability in the link is a requirement.

Other often-cited advantages associated with fiber optic links include (i) the available bandwidth of over 10,000 GHz, (ii) the reduced size of cable, where sub-millimeter diameters of optical fibers compare to 3–10 mm or larger diameter coaxial cables, (iii) the associated reduction in weight if one can minimize the protective materials needed for cabling, (iv) nonconductive or nonmetallic elements, making the fiber useful in cases where electrical isolation between transmitter and receiver is needed, (v) environmental advantages such as being submersible in fluids, liquid nitrogen, and so on, and (vi) being impervious to corrosion. Analog fiber optic links afford additional less-obvious advantages that are difficult or impossible to achieve electrically. These features include the ability to achieve variable true time delay or RF signal multiplexing. For the latter, the advantages of bundling small fibers into close proximity within a single cable allows for a reduction in the temperature dependence between fiber links (Roman et al. 1998a). This allows for better phase tracking among multiple fiber links, which may be used in phased array applications. As an alternative to multiple fibers, the exceptionally wide bandwidth in the fiber can be used to multiplex numerous RF signals onto one fiber link using different optical carriers. Such multiplexed links and the associated nonlinearities were first studied as a means to distribute cable television channels (Phillips and Ott 1999) and later for higher frequency microwave signals from antenna arrays (Campillo et al. 2003). Many of these advantages and their impact on link performance are discussed throughout this text.

1.2 ANALOG VERSUS DIGITAL FIBER OPTIC LINKS

The RF photonics technology that exists today would not be possible if it were not for the use of fiber optics in digital communication systems. The use of optical fiber to transport digital bits of information across the globe has fundamentally changed the way the world communicates. The Internet and an associated thirst for bandwidth have necessitated the rapid development and deployment of multichannel fiber optic data links to squeeze every last bit of information capacity from a single strand of fiber. An additional benefit of the widespread use of optical fiber for telecommunications is the availability of a vast array of components, many of which can be leveraged for microwave photonics.

Economies of scale and the commoditization of many of these devices have reduced the cost of analog links, except in those cases where specialized components are needed that have no dual use in digital systems.

The differences between analog and digital optical communication links can be substantial. In the digital domain, ones and zeroes can be encoded into optical links as groups of photons (an optical pulse) or the absence of photons. Whether the one or the zero is associated to the actual pulse is not relevant. Noise and timing uncertainty can corrupt the signal during modulation, propagation, and/or detection. So long as the noise and timing uncertainty are small, an integrator can accurately distinguish a pulse from the absence of a pulse using a threshold-like decision in a given time window. In early optical communication links, electrical regenerators periodically removed the noise and timing uncertainty and regenerated the information, thus allowing for propagation over very long distances. In contrast, analog systems must account for the presence of or minimize the effects of this noise and timing uncertainty. In many digital systems today, electronic regenerators are minimized or avoided altogether due to cost implications. Therefore, many long-haul digital communication links are essentially analog, in the sense that the quantization occurs at the link output after transmission.

To expand on this point, Figure 1.9 shows a block diagram of a typical long-haul digital communications link. A digital signal (sequence of ones and zeroes) is input to an E/O converter. Since the attenuation over the entire length of propagation would not allow for detection with a low error rate, the signal must be amplified periodically by several optical amplifiers, typically erbium-doped fiber amplifiers (EDFAs). At the end of the link, O/E conversion returns the waveform to the electrical domain for processing with electronics. The input digital waveform (shown on the middle left) is a series of ones and zeroes denoted by two voltage states. This is simply a baseband RF waveform and can be represented by its Fourier transform or equivalently its spectral content as shown in the lower left plot. A periodic pseudorandom non-return-to-zero (NRZ) waveform has a spectral content of individual lines having an amplitude envelope of a $\sin c^2(f)$ function with frequency spacing that is the inverse of the pattern length (Redd and Lyon 2004). Also shown in Figure 1.9 are noise levels. At the output of the link, noise is added due to the amplification stages. In this illustration, the fundamental clock frequency associated with the bit rate has been enhanced as might occur when a small level of chromatic dispersion in the link causes pulse broadening. Such a “digital” link