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Mohammed N. Islam (Ed.)

Raman Amplifiers for Telecommunications 1

Physical Principles

Foreword by Robert W. Lucky

With 222 Figures

Springer

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To my loving wife,
Nasreen

Foreword

I remember vividly the first time that I heard about the fiber amplifier. At that time, of course, it was the erbium-doped fiber amplifier, the predecessor of the Raman amplifier that is the subject of this book.

It was an early morning in a forgotten year in Murray Hill, New Jersey at one of our Bell Labs monthly research staff meetings. About twenty directors and executive directors of research organizations clustered around a long table in the imposing executive conference room. Arno Penzias, the vice president of research, presided at the foot of the table.

Everyone who participated in those research staff meetings will long remember their culture and atmosphere. Arno would pick an arbitrary starting point somewhere around the table, and the designated person would head to the front of the table to give a short talk on "something new" in his or her research area. This first speaker would invariably fiddle helplessly with the controls embedded in the podium that controlled the viewgraph projector, but eventually we would hear machinery grinding in the back room as a large hidden mirror moved into place. We would all wait quietly, arranging and choosing our own viewgraphs from the piles that lay on the table in front of every participant.

The rules for the staff meeting were that each speaker was allowed seven minutes and three viewgraphs. However, in spite of Arno's best efforts to enforce this regimen, everyone took too long and used too many viewgraphs. Various attempts at using loud timers and other incentives all failed. No one could give a respectable talk on a research topic for which they had passionate feelings in seven minutes.

Another rule was that anyone could forfeit his talk by simply saying, "I pass." This forfeiture was always accepted without comment, but new directors always asked their friends about whether this would constitute a black mark against their performance. No one knew for sure, but rumor had it that it was unwise to pass unless you were truly destitute of material. After all, the implication would be that there was nothing new in your research organization for the last month—not a good indication of your management skills.

With no one passing, and everyone speaking too long, these staff meetings sometimes seemed endless. Computer scientists would talk about new constructs in software, systems people would talk about new techniques for speech recognition, physicists would talk about some new laser, chemists would show diagrams of new organic materials, and so forth. It didn't take long for each talk to exceed the understanding of most listeners of whatever specialty was being discussed. I always left with a profound sense of the limitations of my own knowledge, but with an exhilarating inkling into the unfolding of science. It was, perhaps, the best of the old research model in Bell Labs, and in retrospect I can say that in this new competitive world I miss those old scientific-style management meetings.

It was in such a meeting that I first heard about the fiber amplifier. I don't know whether I had been paying attention, but I was immediately galvanized by the implications of this new discovery. One word came to me and blazed across my mind: that word was "transparency."

Surprisingly, in my experience I am not always immediately enthusiastic about a new technology upon initial exposure. One might think that the potentials of great breakthroughs are self-evident, but that does not seem to be the case. When I first heard about the invention of the laser, I had no premonition that lasers would become the primary instrument of the world's telecommunications traffic. When one of the inventors of public key cryptography told me his idea for having two keys, I scoffed at the naiveté of his concept. I remember thinking on first hearing about what is now the principal algorithm for data compression that I thought it was only a theoretical exercise. So my track record for such insights is not altogether good.

However, with the fiber amplifier I went to the other extreme. I foresaw a dramatic revolution in communications. I spoke up at the staff meeting that morning to say that this invention would transform the architecture of communications networks. This would lead to transparent networks, I said, and that this would not necessarily be good for AT&T. I got carried away with this vision, and went on to say that private networks could have their own wavelengths traveling transparently through the network, untouched by the common carrier in the middle. One private network might have "blue" light (figuratively speaking, of course, because we're not talking about visible wavelengths) whereas another would have "green." I foresaw a plug on the wall that passed only the chosen wavelength, which would be owned exclusively by that particular customer's network. AT&T would thus be deprived of the opportunity to process signals for value-added services. AT&T, in fact, wouldn't have any idea what was packed into those wavelengths.

Well, that hasn't exactly happened, but today's optical networks are moving towards increased transparency, and Raman amplifiers will accelerate this trend. The advantages of transparency are compelling. A great many constituent signals can be amplified cheaply in one fell swoop. More importantly, this amplification is independent of the bit rates, protocols, waveforms, multiplexing, or any other particulars of the transmission format. The design isn't "locked in" to any specific format, and as these details change, the amplification remains as effective as ever. In the case of the Raman amplifier, the bandwidth is so enormous that adjectives seem inadequate to describe its potential for bulk amplification.

Transparency in the network is so attractive that probably the only reason it isn't done is that it is so difficult to achieve. One reason is, of course, the necessity for periodically unbundling the signal to add or drop subcomponents. In the digital world this has usually meant a complete demultiplexing and remultiplexing of the overall signal, an expensive operation. The optical world opens up the possibility of selective transparency for certain wavelengths whereas others are unpacked to do add-drop multiplexing.

So network topology sets limits on transparency. But the other reason transparency is hard to achieve is the implicit accumulation of impairments as a signal incurs successive amplifications. It is ironic that the telephone network was essentially transparent for the first half-century of its existence. Until 1960 the long-haul transmission systems used analogue amplification to boost levels as the signal traversed the nation. The invention of the triode vacuum tube enabled the first transcontinental transmission system to be deployed in the 1920s. It was a marvelous feat to be able to send a band of signals 3000 miles across the country, passing through many amplifiers, accumulating noise and distortion along the way, but still providing intelligible speech at the other end. Some older readers will remember when long distance phone calls sounded crackly and "distant." Now, of course, it is impossible to tell how far away a connection is. They all sound local, because of digital transmission.

Digital transmission was the triumph of the 1960s. Though now it seems obvious, engineers found the philosophy of digitization hard to grasp for several decades after the invention of pulse code modulation by Reeves in 1939. There is a trade-off here: bandwidth against perfectibility. A 3 kHz voice signal, for example, is transformed by an analogue-to-digital converter into a 64,000 kbps stream of bits, greatly expanding the necessary transmission bandwidth. However, this digital signal can be regenerated perfectly, removing noise and distortion periodically as necessary. A miracle is achieved as the bits arrive across the country in the same pristine form as when they left.

So it was that all long distance transmission was converted to digital format. The introduction of the first lightwave transmission systems hurried this change, inasmuch as lightwave systems were deemed to be "intrinsically digital" because of their nonlinearities and the lack of amplifiers. No one cared much at the time—the early 1980s—but the entire design of the network was predicated on the transmission of 64 kbps voice channels. The multiplexing hierarchy, the electronic switching, the synchronization and timing, and the transmission format assumed that everything was packaged into neat little voice channels. That, of course, was before the rise of the Internet.

Now optical amplification has reversed this trend of the last half-century towards digitization based upon a hierarchy of voice signals. It isn't just that optical amplifiers have an enormous bandwidth. They do something those old triode vacuum tubes could never do: they amplify without substantially increasing the noise and distortion of the signal. Raman amplifiers are particularly good in this way. Moreover, because Raman amplification is distributed across the whole span of the fiber, the signal level never drops as low as it does when discrete amplifiers are employed. In a system using discrete amplifiers the signal level is at its lowest and most vulnerable right before the point of amplification.

Back at that research staff meeting I was concerned about the implications of transparency to the architecture of the network. A transparent network is, by definition, a "dumb" network. It doesn't do anything to the signal; it can't, because it doesn't know what the signal is. As an AT&T employee, that sounded threatening. As an Internet user, that sounded empowering. The Internet, after all, was designed around the so-called end-to-end principle. In the architecture of the Internet, intelligence is at the periphery of the network, and the network is as minimally intrusive as is necessary to achieve interconnection. It is an extremely important philosophical principle that was just beginning to be understood in the 1980s. Since then the argument has raged, and the concept of a "stupid" network has been put forward by a number of Internet designers as the ultimate desired objective. If that is so, then the optical amplifier has made possible the ultimate stupid network.

I can't leave this foreword without mentioning another observation on perhaps a more personal level. Raman amplifiers epitomize for me the transformation of communications from a world of electrical circuits to one of quantum mechanical phenomena. Of course you could argue that transistors themselves depend on quantum mechanical principles, and surely the laser does, and so forth. But for many practical and design purposes these devices could be modeled with traditional circuit equivalents. Since then, however, photonics has increasingly become a showpiece of modern physics. The erbium-doped fiber amplifier had to be understood as a quantum interaction of light with the erbium atom. Raman amplifiers, by contrast, involve the interaction of light with a material structure. We descend ever more into the realm of quantum phenomena, into a world of small and impressive miracles.

A number of my friends and associates at Bell Labs have contributed to this technology and even to this particular book. I'm very proud of the work that they and their peers in academia and other industries have done in the creation of photonics technology. I've seen it grow around me and have taken vicarious pride in their accomplishments. Sometimes I tell people that, yes, I know the inventors of this or that great technology, even though I may not have realized at the time the significance of the invention. In the case of Raman amplifiers I remember learning about Raman effects as one of the impairments to be overcome in optical transmission. Researchers in my organization were even then experimenting with Raman amplification, and although there was a glimmer of potential, I can't say that I was aware of what their future might bring. Perhaps now its day has come, and that's what this book is all about.

Robert W. Lucky
Fair Haven, New Jersey
March 2003

Preface

Technologies for fiber-optic telecommunications went through a major growth period—some might even say a revolution—roughly during the years 1994 to 2000. This growth came about due to the convergence of several market drivers and technologies. First were data traffic and the Internet, the key drivers of the demand for bandwidth. Prior to the explosion of data traffic and the Internet, voice traffic only grew at an average of 4% a year. The Internet, on the other hand, grew 100% a year or more starting in 1992 and sustained this phenomenal growth rate at least through about 2001. The second was the advent of the optical amplifier, which served the role in optical networks that the transistor had played in the electronics revolution. The optical amplifier was key because it allowed the simultaneous amplification of a number of channels, as opposed to electronic regenerators that operated channel by channel. The third technology was wavelength-division-multiplexing (WDM), which made a single strand of fiber act as many virtual fibers. WDM has allowed the capacity of fibers to be increased by more than two orders of magnitude over the past few years, providing plenty of bandwidth to fuel the growth of data traffic and the Internet. WDM served the role in optical networks that integrated circuits had played in the electronics revolution. Just as the transistor permitted the revolution associated with integrated circuits in electronics, the optical amplifier permitted the revolution associated with WDM in optical networks. Because a number of channels could be simultaneously amplified, the cost of deploying more wavelengths in WDM was gated by the terminal end costs rather than the regenerator costs. Hence far more cost-effective networks became available with the combination of optical amplifiers and WDM.

Raman amplification has been one of the optical amplifier technologies that had a slow start, but then experienced a wide deployment with increasing performance needs of optical networks. It would be reasonable to assume that almost every new or upgraded long-haul (∼300 to 600 km between regenerators) and ultra-long-haul (>600 km between regenerators) will eventually deploy some form of Raman amplification technology. Any deployment concerns about discrete or distributed Raman amplification have been outweighed by the performance improvements permitted with Raman amplification. For example, distributed Raman amplification improves noise performance and decreases nonlinear penalties in WDM networks, thereby alleviating the two main constraints in dispersion-compensated, optically amplified systems. The improved noise performance can be used to travel longer distances between repeaters or to introduce lossy switching elements such as optical add/drop multiplexers or optical cross-connects. Discrete and distributed Raman amplifiers are wavelength agnostic, with the gainband being determined by the pump distribution. Also, discrete Raman amplification can efficiently be integrated with dispersion compensation. Hence, Raman amplification permits wide bandwidth and long reach simultaneously. For instance, commercial systems in 2002 provide 240 channels at 10 Gb/s over 100 nm bandwidth (capacity of 2.4 Tb/s) over 1500 km with static optical add/drop multiplexers at every inline amplifier site (roughly every 80 km). Of course, if less bandwidth is required, then the unrepeated distance can be even longer.

Although stimulated Raman scattering (SRS) dates back to 1928 [7], it was first studied in optical fibers by Roger Stolen and coworkers in 1972 [10, 9]. Much of the physics of Raman amplification was explored through the 1970s and early 1980s. Then, in 1984 Linn Mollenauer, Jim Gordon, and I suggested the use of Raman amplification in WDM soliton systems [5, 6]. We demonstrated the concept using color center lasers as the pump lasers, and there was a flurry of research on Raman amplification in fiber systems from about 1984 to 1988. However, by 1988 it became clear that erbium-doped fiber amplifiers (EDFAs) were closer to practical deployment, and the Raman work was mostly dropped in favor of rare earth-doped amplifiers. Admittedly, it was a bit difficult to imagine how to put large tabletop lasers such as color center lasers in a central office, in a hut, or under the sea.

Although it seemed that EDFAs would never be displaced as optical amplifiers in fiber-optic systems, by 1997 the scene began to change. Work particularly at Lucent Technologies by Steve Grubb, Per Hansen, Andy Stentz, and others began to show the promise of Raman oscillators pumped by cladding-pumped fiber lasers [1, 2, 4, 3, 8]. I realized the big payoff would be not in oscillators but in Raman amplifiers, and I spunoff from the University of Michigan a startup company called Xtera Communications. Xtera began by trying to develop S-band subsystems (Chapter 10), and later we redirected the business plan to a wideband, long-reach, all-Raman system (Chapter 14).

The key thing to understand is that stimulated Raman amplification had not changed. It was the technology required to make Raman amplifiers that had changed. The most fundamental change was the development and commercialization of practical, high-powered, laser diodes. Although we believed that commercial Raman amplifiers would require cladding-pumped fiber lasers, by 1999 it became clear that laser diodes with sufficient power would be available. This was an extremely important development because it would reduce the cost and size of Raman amplifiers while increasing their reliability. Second, dispersion-compensating fibers (DCF) were being commercialized for use with 10 Gb/s systems. It turns out that the DCF is an excellent gain medium for discrete Raman amplifiers, permitting the integration of dispersion compensation with optical amplification. Finally, all of the required passive components became available at least with fiber pigtails and with the ability to handle high pump powers.

By 2000, Raman amplified systems were becoming commercially available. Several startup companies (e.g., Corvis, Qtera, Xtera) were using Raman amplification as their differentiator. Even the stalwarts of the industry had to take notice of this important technological development. For example, Nortel Networks acquired Qtera, and Lucent Technologies began to develop their all-Raman system, which became commercially available in 2002. It finally looked as if Raman amplification had made inroads in long-haul and ultra-long-haul systems. The noise figure improvement of up to 7 dB was simply too large a system margin to ignore!

With heavy research and development of Raman amplified systems between 1997 and 2002, it would be fair to say that the physics and applications of Raman amplifiers were pretty well understood, at least in the arena of telecommunications. The Raman "buzz" was out there, and telecommunications engineers were constantly asking for a "good reference" that they could read to understand Raman amplification. Raman amplifiers were about to leave the eclectic world of research laboratories and PhDs and perhaps enter the commercial Main Street, and a book that summarized the key physical principles and applications was needed. After all, it would be difficult to deploy and maintain that which was unknown. Therefore, at OFC 2002 I finally agreed to put together this volume, *Raman Amplifiers for Telecommunications*.

For me the assembling of this book is another important step on a long journey. As a graduate student and when I first joined AT&T Bell Labs between 1983 and 1987, we were convinced that Raman amplification was going to be important. At MIT I worked with Linn Mollenauer and Jim Gordon on WDM soliton systems using Raman amplification, and then when I first joined Bell Labs I worked on Raman oscillators and amplifiers. Almost a decade later, I spent five years from 1997 to 2002 transferring to commercialization an all-optical, all-Raman amplified system through Xtera Communications. Now that Raman amplification is finally prime-time for systems, it is necessary to organize, articulate, and share the know-how so that telecommunications and systems engineers can deploy and exploit the technology.

Acknowledgments

This book was written and assembled while I was at Xtera Communications, on a leave of absence from the University of Michigan in Ann Arbor, as well as the first year after I returned to the University. Thanks are due to Professors Richard Brown and Duncan Steel at the University for permitting me to complete this book. Also, I am particularly indebted to Dr. Jon Bayless and Carl DeWilde for encouraging me to put this book together and having the foresight to understand the broader impact that a startup could have by allowing this endeavor.

Many at Xtera Communications worked on Raman amplification and helped in composing this volume. In particular, Amos Kuditcher helped significantly on Chapters 10 and 14. Special thanks are due to Monica Villalobos, without whose help this book could never have been written. Monica kept the process moving forward throughout the year with her usual methodical and professional style. She kept contact with all of the authors, collected all of the chapters, and helped in the hand-off to the

publishers. I think that all of my coauthors would agree that Monica was a pleasure to work with throughout the process.

Finally, I am deeply appreciative of the love, support, and encouragement from my wife, Nasreen, and sons, Sabir and Shawn. The only regret I have in putting this book together is the time it took away from my family.

Mohammed N. Islam
Ann Arbor, Michigan
January 2003

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Quick Summary of Book

The book is organized into two volumes with three sections. Volume 1 begins with a chapter entitled "Overview of Raman Technologies for Telecommunications." The first major section (Volume 1, Section A), Raman Physics, contains eight chapters (Chapters 2–9). The second section (Volume 2, Section B) on Subsystems and Modules contains five chapters (Chapters 10–14). Finally, the third section (Volume 2, Section C), Systems Design and Experiments, contains an additional five chapters (Chapters 15–19). Almost half of the book is dedicated to Raman physics, because these are the principles that will remain time invariant. This is covered completely in Volume 1. The second section, Subsystems and Modules, describes applications of Raman technology that will be fairly time invariant, although the details and data of the applications will continuously evolve. Finally, the last section, Systems Design and Experiments, represents a snapshot of the state-of-the-art system demonstrations as of early 2003. This is the section that must necessarily change with time, but at least it can provide a good basis for comparison or updating from 2003. It is important to go all the way from basic physics to systems because they are intimately linked. The basic physics determines what can or cannot be done, and it points to the differential advantages that Raman amplification provides. On the other hand, the systems design and experiments ultimately define what is worth doing and where performance should be optimized. Fortunately, Raman amplification is very rich with physical principles as well as being one of the key enabling technologies for long-haul and ultra-long-haul submarine, terrestrial, soliton, and high-speed systems.

In selecting the topics to be covered in this book as well as the authors to invite, a broad, diverse, and insightful view was sought. As an example, the authors were chosen from industrial labs as well as universities. The industrial laboratories represented include Corning, Furukawa, Lucent Technologies, Nippon Telephone and Telegraph, Nortel Networks, OFS Fitel, Siemens, Tyco Telecommunications, and Xtera Communications. Also, the authors represent the international nature of Raman technology, with contributions from the United States, Europe, Japan, and Russia. Furthermore, young rising stars were invited to contribute chapters as well as the "giants in the field," starting with Roger Stolen, Linn Mollenauer, and Evgeny Dianov.

It is an honor that so many key researchers in Raman technology accepted the invitation to contribute to this book. The invitation was extended to researchers who have made significant contributions to the technology and whose work has consistently represented the highest quality and deepest insight. Obviously there are many other excellent researchers in the field, but the intent was to cover the main issues in Raman physics, subsystems and modules and systems design and experiments within the limited space of two volumes.

The book begins with "Overview of Raman Technologies for Telecommunications," which I authored (Chapter 1). Then, the physics section opens with a chapter by Stolen, "Fundamentals of Raman Amplification in Fibers" (Chapter 2), which is fitting since he did much of the original groundbreaking work on Raman amplification in fibers. Noise is a very important aspect of any optical amplifier, and Fludger contributes two chapters on the topic: "Linear Noise Characteristics" (Chapter 4) and "Noise due to Fast Gain Dynamics" (Chapter 8). The most significant technological development for commercial Raman amplifiers is the increase in laser diode power, and Namiki et al., in Chapter 5 describe "Pump Laser Diodes and WDM Pumping." The other major technological development is the availability of new fibers with efficient Raman gain, and two chapters are dedicated to this topic: in Chapter 6 Grüner-Nielsen and Qian describe dispersion compensating fibers for Raman applications, and in Chapter 7 Dianov describes more forward-looking work on new Raman fibers. The simplest Raman amplifier uses CW pumps and a counterpropagating geometry (i.e., where the pump and signal propagate in opposite directions). However, the performance of this basic Raman amplifier can be improved by a number of emerging techniques. In Chapter 3, Grant and Mollenauer describe the use of time-division multiplexing of pump wavelengths. Then, in Chapter 9 Radic discusses and compares forward, bidirectional, and higher-order Raman amplification.

In the second section, "Subsystems and Modules," four types of Raman devices are covered: discrete (or lumped) amplifiers, distributed amplifiers, lasers, and a combination of discrete and distributed amplifiers. In Chapter 10 I review work on discrete or lumped Raman amplifiers to open up new wavelength windows, particularly in the short wavelength S-band. Then, Headley et al. review in Chapter 11 work on Raman fiber lasers or oscillators. Next, in Chapter 12, Evans et al. discuss distributed Raman transmission, applications, and fiber issues. One of the most important applications of combined discrete and distributed amplifiers is to broadband transmission systems. One way to achieve the broadband amplifier is to combine erbium-doped fiber amplifiers with Raman amplifiers, and in Chapter 13 Masuda describes hybrid EDFA/Raman amplifiers. Another route to a broadband system is to use all-Raman discrete and distributed amplifiers, and in Chapter 14 on wideband Raman amplifiers I along with coworkers at Xtera illustrate this approach.

The third section of the book focuses on system design and experiments. Some of the challenges of the Raman effect are covered in the first two chapters, and system deployments of Raman amplifiers are discussed in the following three chapters. In Chapter 15 Bromage et al. detail multiple path interference and its impact on system design. Then, in Chapter 16 Krummrich discusses Raman impairments in WDM systems. As examples of areas where Raman amplifiers are a key enabling technology, three system experiments are included. First, in Chapter 17 Kidorf et al. describe the use of Raman amplifiers in ultra-long-haul submarine and terrestrial applications. Then, in Chapter 18 Mollenauer discusses ultra-long-haul, dense WDM using dispersion-managed dolitons in an all-Raman system. Finally, in Chapter 19 Nelson and Zhu illustrate 40 Gb/s Raman-amplified transmission.

Survey of Chapters

VOLUME 90/1

Overview of Raman Amplification in Telecommunications (Chapter 1)

As an overview for the book, this chapter surveys Raman amplification for telecommunications. It starts with a brief review of the physics of Raman amplification in optical fibers, along with the advantages and challenges of Raman amplifiers. It also discusses some of the recent technological advances that have caused a revived interest in Raman amplifiers. Then, distributed and discrete Raman amplifiers are described. Distributed Raman amplifiers improve the noise figure and reduce the nonlinear penalty of the amplifier, allowing for longer amplifier spans, higher bit rates, closer channel spacings, and operation near the zero dispersion wavelength. Discrete Raman amplifiers are primarily used to increase the capacity of fiber-optic networks. Examples of discrete amplifiers are provided in the 1310 nm band, the 1400 nm band, and the short-wavelength S-band.

Section A. Raman Physics

Fundamentals of Raman Amplification in Fibers (Chapter 2)

Raman scattering was first published by C.V. Raman in 1928, and he was awarded the 1930 Nobel Prize for the discovery. In 1972 stimulated Raman scattering was first observed in single-mode fibers, and the Raman gain coefficient was also measured that same year. The chapter focuses on various treatments of the Raman interaction, which can appear to be quite different. The quantum approach treats the problem as a transition rate involving photon number. In the classical approach, the Raman effect is a parametric amplifier with an interaction between signal, pump, and vibrational wave. Finally, the Raman interaction itself can be traced to a small time delay in the nonlinear refractive index. This chapter compares and contrasts these various treatments of the Raman effect in optical fibers. Also, a fundamental treatment of noise in fiber Raman amplifiers is included.

Time-Division Multiplexing of Pump Wavelengths (Chapter 3)

This chapter describes an approach to Raman pumping that uses time-division multiplexing of the pump wavelengths. TDM pumping has several advantages over CW pumping such as efficient gain leveling with a “smart” pump, the elimination of four-wave mixing between pumps, and the reduction of pump-to-pump Raman interactions. This technique only works with backward Raman pumping, where the pump and signal are counterpropagating. The rate of TDM pumping needs only to exceed 1 MHz, so electronic components for these speeds are widely available and very inexpensive. However, TDM Raman pumping does introduce a new set of problems. The higher gain for signal propagating in the backward direction leads to a larger backward spontaneous Raman noise level. Consequently, Rayleigh scattering of the backward propagating noise can significantly increase the forward noise level under high gain conditions.

Linear Noise Characteristics (Chapter 4)

Spontaneous emission is the inevitable consequence of gain in an optical amplifier. In this chapter, the definition of noise figure is shown to be useful only in characterizing shot noise and signal-spontaneous beat noise. The noise characteristics of both discrete and distributed Raman amplifiers are presented. Also, a general model that accurately predicts both signal propagation and the buildup of amplified spontaneous emission is discussed and compared to measurements. Further measurements and analysis of broadband Raman amplifiers show a clear dependence on temperature, which places a fundamental limit on their performance. Interactions between the pump wavelengths are also shown to play an important role, giving better system performance to longer signal wavelengths at the expense of the shorter wavelengths. Finally, an analysis of the relative linear noise performance of different transmission fibers is presented.

Pump Laser Diodes and WDM Pumping (Chapter 5)

This chapter discusses issues surrounding the pump laser diodes for broadband Raman amplifiers, which range from fundamentals to industry practices of Raman pump sources based on so-called 14XX nm pump laser diodes. The chapter also describes the design and issues of wavelength-division-multiplexed pumping for realizing a broad and flat Raman gain spectrum over the signal band. In addition, practical Raman pump units are illustrated, and the chapter also provides insights into ongoing issues on copumped Raman amplifiers and their pumping sources. The pump laser diodes discussed are InGaAsP/InP GRIN-SCH strained layer MQW structure with BH structure, which are the most widely used in the industry.

Dispersion-Compensating Fibers for Raman Applications (Chapter 6)

Dispersion-compensating fibers are the most widely used technology for dispersion compensation. Also, DCF is a good Raman gain medium, due to a relatively high germanium doping level and a small effective area. Dispersion-compensating Raman amplifiers integrate two key functions, dispersion compensation and discrete Raman amplification, into a single component. Use of DCF for broadband Raman amplifiers raises new requirements for the properties of the DCF including requirements for gain, double Rayleigh scattering, and broadband dispersion compensation. Dispersion slope compensation is now possible for all types of transmission fibers, and the next challenge for broadband dispersion compensation is dispersion curvature. Dispersion-compensating Raman amplifiers have been realized with high-gain, low-noise figure and low multipath interference arising from double Rayleigh back scattering.

New Raman Fibers (Chapter 7)

Standard transmission fibers with silica core doped with a small concentration of GeO_2 have a low value of the Raman gain and a peak Raman gain at a frequency shift of about 440 cm^{-1}. However, for a number of applications such as discrete Raman amplifiers and Raman fiber lasers, special fibers with much higher Raman gain and/or various Raman frequency shifts are often required. Early experiments show that low-loss, high GeO_2- and P_2O_5-doped silica fibers could be promising fiber gain Raman fibers. For example, phosphor-silicate glass has two Raman scattering bands shifted by 650 cm^{-1} and 1300 cm^{-1}, and the cross-section for these bands is 5.7 and 3.5 times higher compared to silica. However, these fibers have met with serious challenges during fabrication by well-developed techniques. Nonetheless, at present germano-silicate and phosphor-silicate Raman fibers are being widely used for constructing CW Raman fiber lasers, which can cover the whole spectral range of 1.2 to 1.75 microns. These CW medium power (1 to 10 W) lasers are a convenient laser source for pumping optical fiber amplifiers and some lasers.

Noise due to Fast Gain Dynamics (Chapter 8)

The time response of the Raman effect is associated with the vibrations of the molecules in the gain medium and is on the order of several hundred femtoseconds. Compared to current data rates, this energy transfer is practically instantaneous, resulting in very fast gain dynamics. In a copumped Raman amplifier, the gain dynamics are averaged due to chromatic dispersion between pump and signal wavelengths. This lessens the impact of the fast physical process and results in a more improved system performance than would otherwise be expected. In a counterpumped Raman amplifier, the different propagation directions of pump and signals average the gain over the cavity length. This much stronger averaging greatly reduces system penalties in counterpumped amplifiers. In this chapter models are developed for co- and counterpumped Raman amplifiers that quantify both the transfer of relative intensity noise from the pump to the signal and also the signal-to-signal crosstalk, mediated by the pump (crossgain modulation). In addition, the system impact in terms of Q penalty is determined, as well as determining the actual energy transfer from pumps to signals and from crossgain modulation.

Forward, Bidirectional, and Higher-Order Raman Amplification (Chapter 9)

Distributed Raman amplification can be achieved by optical pumping at either end of the fiber. In a unidirectional transmission line, all signals travel in the same direction.

In contrast, bidirectional transmission can be used to realize two-way traffic within a single fiber line: counterpropagating signal traffic is launched and received at the opposite ends of the optical link. A bidirectionally pumped fiber span can support both uni- and bidirectional signal transmission. A unidirectionally pumped span, however, almost exclusively supports unidirectional signal traffic. This chapter explores and compares forward, bidirectional, and higher-order Raman amplification. Higher-order pumping refers to the introduction of shorter-wavelength pumps that are used to pump the pump; that is, the higher-order pump amplifies the first-order pump, which in turn pumps the signal band. Different pumping schemes provide different levels of performance, but each scheme has a trade-off of performance versus pump laser restrictions.

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Section B. Subsystems and Modules

S-Band Raman Amplifiers (Chapter 10)

The design, implementation, and issues associated with S-band amplification are discussed in this chapter, with a special emphasis on lumped Raman amplifiers (LRAs). LRAs can be used in a split-band augmentation strategy with new or already deployed C- and/or L-band systems, which are usually amplified with EDFAs. To open up the S-band, the key enabling technology is the appropriate optical amplifier. Raman amplifiers appear to be a practical solution to the S-band amplifier, and they are a mature technology ready for deployment. Utilizing silica fiber as the gain medium, Raman amplifiers can be readily fusion spliced with the fiber used in the transport infrastructure. LRAs have also been demonstrated with performance on a par with commercial C-band EDFAs in terms of gain, noise figure, and bandwidth. In addition, LRAs can be implemented efficiently using DCF, which means that the lumped amplifier can be integrated with the dispersion compensation. The major challenge of Raman amplifiers has been their lower efficiency than EDFAs, but this discrepancy is narrowing through better gain fibers, higher laser diode pump powers, and the inherent better slope efficiency for Raman amplifiers at higher channel count. The bulk of this chapter focuses on the issues and experimental demonstration of S-band LRAs in fiber-optic transmission systems.

Raman Fiber Lasers (Chapter 11)

This chapter focuses on cascaded Raman fiber lasers (RFL), which use the stimulated Raman scattering in optical fibers to shift the wavelength of light from an input pump laser to another desired wavelength. Devices at almost any wavelength can be made by proper choice of a pump wavelength, and by cascading the pump through several Raman shifts. Although RFL had been demonstrated since the 1970s, the advent of fiber Bragg gratings made the devices practical. A broadband flat Raman gain profile can be obtained using multiple pump wavelengths, and it is advantageous to have all the required wavelengths emitted from one source. This motivated the development of a multiple wavelength RFL. Single cavities simultaneously lasing from two to six wavelengths have been demonstrated. Finally, distributed Raman amplification techniques have become more sophisticated with the proposed use of higher-order pumping schemes. The use of a RFL is especially suited to this application, inasmuch as large amounts of powers are required at the shortest pump wavelength.

Distributed Raman Transmission: Applications and Fiber Issues (Chapter 12)

The persistent demand for higher performance (capacity, system reach, data rate, etc.) has turned system designers to distributed Raman for its lower noise figure. Today's data-dominated traffic patterns require reach beyond 1000 km, and Raman amplification is one vital tool in pushing out the system reach. This chapter reviews the two most important properties of an optical amplifier—pump efficiency and noise figure—and compares Raman to erbium amplification. The concept of effective noise figure is covered, which leads to a generic system scaling relationship that aids in the prediction of Raman-assisted, system performance improvements. Raman transmission experiments at 10 Gb/s and 40 Gb/s are summarized, and design issues specific to these systems are covered. In addition, dispersion-managed fiber consisting of optical fiber spans that can be optimized for Raman transmission is introduced.

Hybrid EDFA/Raman Amplifiers (Chapter 13)

This chapter describes the technologies needed for cascading an EDFA and a fiber Raman amplifier to create a hybrid amplifier, the EDFA/Raman hybrid amplifier. Two kinds of hybrid amplifiers are defined in this chapter: the "narrowband hybrid amplifier," and the "seamless and wideband hybrid amplifier." The narrowband amplifier employs distributed Raman amplification in the transmission fiber together with an EDFA; this provides low-noise transmission in the C- or L-band. The noise figure of the transmission line is lower than it would be if only an EDFA were used. The wideband amplifier, on the other hand, employs distributed or discrete Raman amplification together with an EDFA. The wideband amplifier provides a low-noise and wideband transmission line or a low-noise and wideband discrete amplifier for the C- and L-bands. The typical gain bandwidth of the narrowband amplifier is ~30 to 40 nm, whereas that of the wideband amplifier is ~70 to 80 nm.

Wideband Raman Amplifiers (Chapter 14)

This chapter describes the design and implementation of wideband Raman amplifiers. All-Raman amplification enables the lowest cost and smallest footprint system, and Raman amplification provides a simple single platform for long-haul and ultra-long-haul fiber-optic transmission systems. Despite a significant list of advantages, a number of challenges exist for Raman amplification, including: pump–pump interactions, interband and intraband Raman gain tilt, noise arising from thermally induced phonons near the pump wavelengths, multipath interference from double Rayleigh scattering, coupling of pump fluctuations to the signal, and pump-mediated signal crosstalk. Fortunately, design techniques exist for overcoming all of these physical limitations, thus allowing for the relatively simple implementation of 100 nm Raman amplifiers. Although commercially available wideband Raman amplifiers have been limited to a bandwidth of 100 nm to date, laboratory experiments have shown amplifiers with much larger bandwidths. Bandwidths greater than 100 nm are usually achieved with such special techniques as new glass compositions or wavelength guard bands around the pump wavelengths. Finally, the application of wideband Raman amplification in high-performance transmission systems is reviewed. For example, an all-Raman amplifier structure with discrete and distributed amplification can give significant advantages of reach and capacity. Such a design has been implemented, and the transmission feasibility of 240 OC-192 channels over 1565 km standard single-mode fiber has been demonstrated

Section C. Systems Design and Experiments

Multiple Path Interference and Its Impact on System Design (Chapter 15)

Up to the end of the 1990s, the main causes of signal degradation in transmission were fiber nonlinearity and amplified spontaneous emission from optical amplifiers. With the advent of Raman amplification in fiber-optic communications systems, another source of signal degradation has become increasingly relevant: so-called multiple path interference or MPI. This chapter focuses on MPI and its impact on receiver and system design. Optical amplification can exacerbate MPI by providing gain for paths that would otherwise have too much attenuation to be significant. Sources of MPI include discrete reflections within or surrounding optical amplifiers, double Rayleigh scattering in optical amplifiers or in the transmission span, and unwanted transverse mode mixing in higher-order mode dispersion compensators. The properties of MPI and Rayleigh scattering are reviewed, and the techniques for measuring MPI level are then described. The impact of MPI on beat-noise limited receivers is discussed, along with techniques for system design optimization.

Raman Impairments in WDM Systems (Chapter 16)

In most chapters of this book, stimulated Raman scattering is invoked intentionally. Pump radiation is coupled into the fiber carrying the signal radiation to generate Raman gain. However, SRS also occurs unintentionally in WDM transmission systems. Due to the large number of channels inside the Raman gain bandwidth, total power can add up to levels where considerable amounts of SRS are generated, with the signal channels acting as pumps. In contrast to the beneficial effects of intentional Raman pumping, the unintended generation of SRS usually degrades system performance. This chapter addresses effects resulting from the unintended invocation of SRS and their impact on WDM signal transmission. A number of system impairments result from the interaction between signal channels due to SRS. Effects with time scales well below the bit period affect the mean values of the individual channel powers. On the other hand, fast interactions between individual bits change the variances of the respective channel powers and can be considered as noise. In addition, some selection criteria for transmission fibers with respect to Raman efficiency are provided.

Ultra-Long-Haul Submarine and Terrestrial Applications (Chapter 17)

Ultra-long-haul (ULH) optically amplified transmission systems (defined in this chapter as those spanning from 1500 to 12,000 km) are some of the most technically challenging systems designed today. Undersea cable systems require ULH, inasmuch as the distance across the Atlantic Ocean is approximately 6000 km and the distance across the Pacific Ocean is approximately 9000 km. For terrestrial networks, the ULH networks are needed because of the change in the nature of the traffic. Until a few years ago, voice traffic dominated the network, and a span distance of 600 km satisfied more than 60% of the connections for voice traffic. However, with the Internet dominating the traffic now, a span distance of 3000 km is required to satisfy 60% of the connections for Internet traffic. In terrestrial systems, the marriage of Raman amplification technology and EDFAs has demonstrated great benefit by expanding the bandwidth of amplifiers, extending the distance between amplifiers, and allowing longer distances to be spanned. For submarine systems where the systems are designed to achieve a desired capacity over often the longest transmission distances, shorter span length (than for terrestrial systems) often has to be chosen. For such shorter spans (~50 km), the benefits of Raman amplification are not nearly as substantial. Presently, the most promising candidate use of Raman amplification in submarine systems is the wideband hybrid Raman–EDFA. For systems that require a very wide bandwidth this seems like an attractive way to more than double the transmission bandwidth without doubling the component count.

Ultra-Long-Haul, Dense WDM Using Dispersion-Managed Solitons in an All-Raman System (Chapter 18)

In an all-Raman-amplified system, dispersion-managed solitons can provide for dense WDM, uniquely compatible with all-optical terrestrial networking, robust and error-free over many thousands of kilometers. This chapter discusses various aspects of system design, including optimal dispersion maps, nonlinear and noise penalties, and typical dense WDM system performance. For example, dispersion-managed solitons are described as well as their special, periodic pulse behavior, their advantages over other transmission modes, and the conditions required to create and to maintain them. Also studied is one serious nonlinear penalty they suffer, viz. the timing jitter from collisions with solitons of neighboring channels. Dispersion-managed solitons, in an all-Raman, dense WDM system at 10 Gb/s per channel, makes a natural and comfortable fit with existing terrestrial fiber spans and can provide for transmission that is robust and error-free out to distances of 7000 km or more. In addition, such transmission is uniquely suited to provide the backbone of an all-optical network.

40 Gb/s Raman-Amplified Transmission (Chapter 19)

High-capacity 40 Gb/s transmission systems offer scalable solutions for future traffic growth in the core network. The challenges of 40 Gb/s systems include optical signal-to-noise ratio, fine-tuned dispersion compensation, and polarization mode dispersion. Raman amplification is likely to be a key driver to ease the noise performance and increase the available bandwidth for 40 Gb/s DWDM systems. New fiber technologies provide high system performance and enable a simple and cost-effective dispersion-compensation scheme. More system margin can also be expected from high-coding-gain forward error correction. Optimized modulation formats and high-speed optoelectronics will make practical deployment of 40 Gb/s DWDM systems possible, facilitating multiple terabit transmission over Mm distance at low cost-per-bit-per-kilometer. The challenges of DWDM transmission at 40 Gb/s are addressed in this chapter, along with the technologies enabling 40 Gb/s terrestrial transmission. Also described are advanced experiments and demonstrations at 40 Gb/s using Raman amplification.

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