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INTRODUCTION

The propagation of light in optical fibers is based on the phenomenon of total internal reflection, which is known since 1854, when John Tyndall demonstrated the transmission of light along a stream of water emerging from a hole in the side of a tank [1]. Glass fibers were fabricated since the 1920s, but their use remained restricted to medical applications until the 1960s. The use of such fibers for optical communications was not practical, due to their high losses (~ 1000 dB/km). However, Kao and Hockham [2] suggested in 1966 that optical fibers could be used in communication systems if their losses were reduced below 20 dB/km. Following an intense activity on the purification of fused silica, such goal was achieved in 1970 by Corning Glass Works, in the United States. Further technological progress allowed the reduction of fiber loss to 0.2 dB/km near the 1550 nm spectral region by 1979 [3]. This achievement led to a revolution in the field of optical fiber communications.

Besides the loss, the fiber dispersion constitutes actually another main problem affecting the performance of an optical communication system. An example of this is the mechanism of *group velocity dispersion* (GVD), which arises as the frequency components of the signal pulse propagate with different velocities, determining the broadening of the pulse. Dispersive pulse broadening and loss both increase in direct proportion to the length of the link. Traditionally, repeater stations have been used at appropriate intervals over long links for detecting, electrically amplifying, filtering, and then regenerating the optical signal. However, such repeaters are complicated and become expensive to use in large quantities. Fiber amplifiers appear in most cases as an attractive alternative to the electronic repeaters. A single amplifier is able to boost the power in multiple wavelengths simultaneously, whereas a separate electronic repeater is needed for each wavelength. This simple fact made feasible the development and deployment of dense wavelength division multiplexed (DWDM) systems, which have revolutionized network communication systems since the 1990s.

The expansion of fiber networks to encompass larger areas coupled with the use of longer distances between amplifiers or repeaters means that higher optical power levels are needed. In addition, the ever-increasing bit rates imply the use of shorter

pulses having higher intensities. Both these changes increase the likelihood of various nonlinear processes in the fibers. In fact, the nonlinearities of fused silica, from which optical fibers are made, are weak compared to those of many other materials. However, nonlinear effects can be readily observed in optical fibers due to both their rather small field cross sections, which results in high field intensities, and the long interaction lengths provided by them, which significantly enhances the efficiency of the nonlinear processes. These nonlinear processes can impose significant limitations in high-capacity fiber transmission systems.

It seems paradoxical that the same nonlinear phenomena that impose several important limitations also offer the promise of addressing the bandwidth bottleneck for signal processing for future ultrahigh-speed optical networks. In fact, electronic devices are not suitable for such systems, due to their cost, complexity, and practical speed limits. All-optical signal processing appears, therefore, as a key and promising technology for improving the transparency and increasing the capacity of future full “photonic networks” [4].

Nonlinear optical signal processing appears as a potential solution to this demand. In particular, the third-order $\chi^{(3)}$ optical nonlinearity in silica-based single-mode fibers offers a significant promise in this regard [5]. This happens not only because the third-order nonlinearity is nearly instantaneous—having a response time typically < 10 fs—but also because it is responsible for a wide range of phenomena, which can be used to construct a great variety of all-optical signal processing devices.

Silica fiber nonlinearities can be classified into two main categories: stimulated scattering effects (Raman and Brillouin) and effects arising from the nonlinear index of refraction. Stimulated scattering is manifested as intensity-dependent gain or loss, while the nonlinear index gives rise to an intensity-dependent phase of the optic field. The first experimental demonstration of fiber nonlinearities was Erich Ippen’s CS₂-core fiber Raman laser in early 1970 [6]. Subsequently, Smith’s theoretical paper on stimulated Raman and Brillouin scattering in silica fibers [7] and the first experimental demonstration of stimulated Raman scattering in a single-mode fiber by Stolen et al. [8] were two landmarks in this field.

Stimulated Raman scattering (SRS) results from the interaction between the photons and the molecules of the medium and leads to the transfer of the light intensity from the shorter to the longer wavelengths. The SRS gain in silica has a wide bandwidth on the order of 12 THz (~ 100 nm at 1.5 μ m) due to its amorphous nature. Thus, SRS can lead to the crosstalk between different WDM channels, becoming the most detrimental of the scattering effects in such systems.

Besides the negative aspect pointed out above, the Raman effect can also find several positive applications. One of the readily apparent advantages of Raman gain in glass fibers was the possibility of constructing wideband amplifiers and tunable oscillators [9]. Indeed, the first SRS work also demonstrated a Raman oscillator using mirrors to provide feedback in a 190 cm fiber [8]. However, the goal of a tunable continuous-wave (CW) fiber Raman laser would have to wait for longer low-loss single-mode fibers. It was not until 1983 that studies of Raman amplification from laboratories around the world began to appear. By the end of the 1980s, the signal-to-noise advantages of Raman amplification appeared to be well understood [10].

However, the lack of efficient high-power fiber-coupled pump lasers prevented the practical use of Raman amplification by that time. After 1988, the lightwave world concentrated on the erbium fiber amplifier, and it was not until 1997 that system experiments using Raman amplifiers started to appear. Following those early demonstrations, the use of Raman amplification in transmission systems has become quite common.

Brillouin scattering originates from the interaction between the pump light and acoustic waves generated in the fiber. In this way, a strong wave traveling in one direction provides narrowband gain, with a linewidth on the order of 20 MHz, for light propagating in the opposite direction. Stimulated Brillouin scattering (SBS) in fibers was observed for the first time in 1972 by Ippen and Stolen [11], who used a pulsed narrowband xenon laser operating at 535.3 nm.

The peak of the Brillouin gain coefficient is over 100 times greater than the Raman gain peak, which makes SBS the dominant nonlinear process in silica fibers under some circumstances. This is particularly the case in fiber transmission systems using narrow-linewidth lasers. SBS can be detrimental to such systems in a number of ways: by originating a severe signal attenuation, by causing multiple frequency shifts in some cases, and by introducing a high-intensity backward coupling into the transmission optics. However, Brillouin gain can also find some useful applications, namely, as an inline fiber amplifier [12,13], for channel selection in a closely spaced wavelength-multiplexed network [14,15], temperature and strain sensing [16,17], all-optical slow-light control [18,19], optical storage [20], and so on.

The intensity-dependent refractive index of silica gives rise to three effects: self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). The SPM effect corresponds to a spectral broadening of the pulse determined by its own power temporal variation. The first observation of this phenomenon in silica fibers occurred in a 1975 experiment by Lin and Stolen [21]. Earlier, Hasegawa and Tappert [22] suggested the existence of fiber solitons, resulting from a balance between SPM and anomalous GVD. Such solitons were indeed observed experimentally by Mollenauer et al. [23] in 1980 and subsequently led to a number of advances in the generation and control of ultrashort pulses [24,25]. The advent of fiber amplifiers fueled research on optical solitons and eventually led to new types of solitons, such as dispersion-managed and dissipative solitons [26–33].

The XPM effect is similar to the SPM effect but the spectral broadening of the pulses is now due to the influence of other pulses propagating at the same time in the fiber. This effect becomes especially important in WDM systems, where a large number of pulses with different carrier wavelengths are usually transmitted in one fiber. Since the bit pattern in the different channels is completely random, the cancellation of this effect through an intelligent system design will be impossible in practice. The XPM appears indeed as the fundamental effect that determines the maximum capacity of optical transmission systems. However, XPM can also be used with advantage in several applications in the area of nonlinear optical processing [34–37].

Due to the FWM effect, beating between two channels at their difference frequency modulates the signal phase at that frequency, generating new frequencies as

sidebands. The occurrence of the FWM phenomenon in optical fibers was observed for the first time by Stolen et al. [38] using a 9 cm long multimode fiber pumped by a double-pulsed YAG laser at 532 nm. In a WDM system, if the channels are equally spaced, the new components generated by FWM fall at the original channel frequencies, giving rise to crosstalk [39–41]. In contrast to SPM and XPM, which become more significant for high bit rate systems, the FWM does not depend on the bit rate. The efficiency of this phenomenon depends strongly on phase matching conditions, as well as on the channel spacing, chromatic dispersion, and fiber length.

Besides its obvious application in generating new frequencies over a broad spectral range, FWM can also be used to amplify signals over a broad band around the fiber zero-dispersion wavelength. Moreover, FWM can be used for nonlinear phase conjugation, frequency conversion, optical switching, generation of squeezed states of light, and as a source of entangled photon pairs [42–53].

Starting in 1996, new types of fibers, known as tapered fibers, photonic crystal fibers, and microstructured fibers, were developed [54–58]. Structural changes in such fibers profoundly affect their dispersive and nonlinear properties. As a result, new phenomena were observed, such as the supercontinuum generation, in which the optical spectrum of ultrashort pulses is broadened by a factor of more than 200 over a length of only 1 m or less [59–62]. The efficiency of the nonlinear effects can be further increased using fibers made of materials with a nonlinear refractive index higher than that of the silica glass, namely, lead silicate, tellurite, bismuth glasses, and chalcogenide glasses [63–66]. Using such highly nonlinear fibers (HNLFs), the required fiber length for nonlinear processing can be reduced to the order of centimeters, instead of the several kilometers long conventional fibers.

This book is intended to provide a comprehensive account of the various nonlinear effects occurring in optical fibers. An overview is given of the impact of these effects on communication systems, as well as of their potential in different applications, particularly for signal processing, pulse generation, and amplification. This book can be roughly divided into five parts. The first part, consisting of Chapters 2–4, presents the basic concepts and equations that will be used in the rest of the book. Chapter 2 provides a review of the fundamental concepts and properties related to light propagation in linear dielectric media. The harmonic oscillator model is used to describe the interaction between an optical wave and the matter. Chapter 3 discusses the basic linear properties of optical fibers in the perspective of their use in communication systems, a special attention being paid to the phenomena of chromatic dispersion and polarization mode dispersion. A brief introduction to nonlinear optics, the derivation of the nonlinear Schrödinger equation, and a discussion of its soliton solutions are presented in Chapter 4.

The second part, consisting of Chapters 5–7, is dedicated to the description of nonlinear effects arising from the intensity-dependent refractive index of optical fibers. Chapter 5 describes the phenomena of self-phase modulation and cross-phase modulation, as well as their impact on communication systems. Chapter 6 deals with the four-wave mixing process, including some important applications of this phenomenon, such as parametric amplification, parametric oscillation, optical phase conjugation, and the generation of squeezed states of light. While both XPM and

FWM appear as *interchannel* nonlinear effects, the nonlinear interaction among the pulses of the same channel is discussed in Chapter 7 in which two *intrachannel* effects are considered: the intrachannel cross-phase modulation (IXPM) and the intrachannel four-wave mixing (IFWM). Both IXPM and IFWM can occur only when the pulses overlap in time, at least partly, during their propagation, as happens in dispersion-managed transmission systems.

The third part, consisting of Chapters 8–10, is dedicated to the topic of optical fiber solitons and their applications. Chapter 8 deals with the use of optical solitons in communication systems, considering both constant dispersion and dispersion-managed fiber links. Other applications and phenomena involving optical solitons are discussed in Chapter 9. The polarization effects on soliton propagation, considering the cases of both constant and randomly varying birefringence, are discussed in Chapter 10.

The fourth part, consisting of Chapters 11 and 12, presents a discussion of resonant fiber nonlinear effects. Chapter 11 is dedicated to the stimulated Raman scattering effect, whereas Chapter 12 deals with the stimulated Brillouin scattering effect. The similarities and main differences between these two effects, the limitations that they impose on communication systems, and some important applications are discussed in both chapters.

The fifth and last part, consisting of Chapters 13 and 14, is dedicated to the description of the more relevant types of highly nonlinear fibers, together with some of their actual applications in nonlinear optical signal processing. Chapter 13 describes silica-based conventional highly nonlinear fibers, microstructured fibers, and fibers made of highly nonlinear materials, as well as some novel nonlinear phenomena that can be observed with them. Chapter 14 highlights the importance of highly nonlinear fibers to realize different functions in the area of optical signal processing, namely, multiwavelength sources, pulse generation, all-optical regeneration, wavelength conversion, and optical switching.

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