Applications of Nonlinear Fiber Optics

SECOND EDITION

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Second Edition

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In the memory of my parents and

for Anne, Sipra, Caroline, and Claire

Preface

Since the publication of the first edition of my book *Nonlinear Fiber Optics* in 1989, this field has virtually exploded. During the 1990s, a major factor behind such a sustained growth was the advent of fiber amplifiers and lasers, made by doping silica fibers with rare-earth materials such as erbium and ytterbium. Erbium-doped fiber amplifiers revolutionized the design of fiber-optic communication systems, including those making use of optical solitons, whose very existence stems from the presence of nonlinear effects in optical fibers. Optical amplifiers permit propagation of lightwave signals over thousands of kilometers as they can compensate for all losses encountered by the signal in the optical domain. At the same time, fiber amplifiers enable the use of massive wavelength-division multiplexing, a technique that by 1999 led to the development of lightwave systems with capacities exceeding 1 Tb/s. Nonlinear fiber optics plays an important role in the design of such high-capacity lightwave systems. In fact, an understanding of various nonlinear effects occurring inside optical fibers is almost a prerequisite for a lightwave-system designer.

Starting around 2000, a new development occurred in the field of *nonlinear fiber optics* that changed the focus of research and led to a number of advances and novel applications in recent years. Several kinds of new fibers, classified as highly nonlinear fibers, have been developed. They are referred to with names such as *microstructured fibers, holey fibers*, or *photonic crystal fibers*, and share the common property that a relatively narrow core is surrounded by a cladding containing a large number of air holes. The nonlinear effects are enhanced dramatically in such fibers. In fact, with a proper design of microstructured fibers, some nonlinear effects can be observed even when the fiber is only a few centimeters long. The dispersive properties of such fibers also are quite different compared with those of conventional fibers, developed mainly for telecommunication applications. Because of these changes, microstructured fibers exhibit a variety of novel nonlinear effects that are finding application in the fields as diverse as optical coherence tomography and high-precision frequency metrology.

The fourth edition of *Nonlinear Fiber Optics*, published in 2007, has been updated to include recent developments related to the advent of highly nonlinear fibers. However, it deals mostly with the fundamental aspects of this exciting field. Since 2001, the applications of nonlinear fiber optics have been covered in a companion book that also required updating. This second edition of *Applications of Nonlinear Fiber Optics* fills this need. It has been expanded considerably to include the new research material published over the last seven years or so. It retains most of the material that appeared in the first edition.

The first three chapters deal with three important fiber-optic components—fiber-based gratings, couplers, and interferometers—that serve as the building blocks of lightwave technology. In view of the enormous impact of rare-earth-doped fibers, amplifiers and lasers made by using such fibers are covered in Chapters 4 and 5. Chapter 6 deals with the pulse-compression techniques. Chapters 7 and 8 has been revised extensively to make room for the new material. The former is devoted to fiber-optic communication systems, but Chapter 8 now focuses on the ultrafast signal processing techniques that make use of nonlinear phenomena in optical fibers. Last two chapters, Chapters 9 and 10, are entirely new. Chapter 9 focuses on the applications of highly nonlinear fibers in areas ranging from wavelength laser tuning and nonlinear spectroscopy to biomedical imaging and frequency metrology. Chapter 10 is devoted to the applications of nonlinear fiber optics in the emerging technologies that make use of quantum-mechanical effects. Examples of such technologies include quantum cryptography, quantum computing, and quantum communications.

This volume should serve well the needs of the scientific community interested in such diverse fields as ultrafast phenomena, high-power fiber amplifiers and lasers, optical communications, ultrafast signal processing, and quantum information. The potential readership is likely to consist of senior undergraduate students, graduate students enrolled in the M.S. and Ph.D. programs, engineers and technicians involved with the telecommunication and laser industry, and scientists working in the fields of optical communications and quantum information. Some universities may opt to offer a high-level graduate course devoted solely to nonlinear fiber optics. The problems provided at the end of each chapter should be useful to instructors of such a course.

Many individuals have contributed to the completion of this book either directly or indirectly. I am thankful to all of them, especially to my students, whose curiosity led to several improvements. Some of my colleagues also helped me in preparing this book. I thank Prof. J. H. Eberly, Prof. A. N. Pinto, and Dr. S. Lukishova for reading the chapter on quantum applications and making helpful suggestions. I am grateful to many readers for their feedback. Last, but not least, I thank my wife, Anne, and my daughters, Sipra, Caroline, and Claire, for understanding why I needed to spend many weekends on the book instead of spending time with them.

Govind P. Agrawal

Rochester, NY
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Contents

Chapter 1

Fiber Gratings

Silica fibers can change their optical properties permanently when they are exposed to intense radiation from a laser operating in the blue or ultraviolet spectral region. This photosensitive effect can be used to induce periodic changes in the refractive index along the fiber length, resulting in the formation of an intracore Bragg grating. Fiber gratings can be designed to operate over a wide range of wavelengths extending from the ultraviolet to the infrared region. The wavelength region near 1.5 μm is of particular interest because of its relevance to fiber-optic communication systems. In this chapter on fiber gratings, the emphasis is on the role of the nonlinear effects. Sections 1.1 and 1.2 discuss the physical mechanism responsible for photosensitivity and various techniques used to make fiber gratings. The coupled-mode theory is described in Section 1.3, where the concept of the photonic bandgap is also introduced. Section 1.4 is devoted to the nonlinear effects occurring under continuous-wave (CW) conditions. The phenomenon of modulation instability is discussed in Section 1.5. The focus of Section 1.6 is on propagation of optical pulses through a fiber grating with emphasis on optical solitons. The phenomenon of nonlinear switching is also covered in this section. Section 1.7 is devoted to related fiber-based periodic structures such as long-period, chirped, sampled, transient, and dynamic gratings together with their applications.

1.1 Basic Concepts

Diffraction gratings constitute a standard optical component and are used routinely in various optical instruments such as a spectrometer. The underlying principle was discovered more than 200 years ago [1]. From a practical standpoint, a diffraction grating is defined as any optical element capable of imposing a periodic variation in the amplitude or phase of light incident on it. Clearly, an optical medium whose refractive index varies periodically acts as a grating since it imposes a periodic variation of phase when light propagates through it. Such gratings are called *index gratings*.

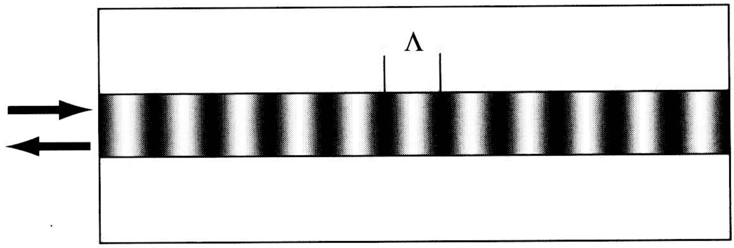

Figure 1.1: A fiber grating. Dark and light shaded regions within the fiber core show periodic variations of the refractive index.

1.1.1 Bragg Diffraction

The diffraction theory of gratings shows that when light is incident at an angle θ_i (measured with respect to the planes of constant refractive index), it is diffracted at an angle θ_r such that [1]

$$\sin\theta_i - \sin\theta_r = m\lambda/(\bar{n}\Lambda), \qquad (1.1.1)$$

where Λ is the grating period, $\lambda/\bar{n}$ is the wavelength of light inside the medium with an average refractive index $\bar{n}$, and m is the order of Bragg diffraction. This condition can be thought of as a phase-matching condition, similar to that occurring in the case of Brillouin scattering or four-wave mixing [2] and can be written as

$$\mathbf{k}_i - \mathbf{k}_d = m\mathbf{k}_g, \qquad (1.1.2)$$

where $\mathbf{k}_i$ and $\mathbf{k}_d$ are the wave vectors associated with the incident and diffracted light. The grating wave vector $\mathbf{k}_g$ has magnitude $2\pi/\Lambda$ and points in the direction in which the refractive index of the medium is changing in a periodic manner.

In the case of single-mode fibers, all three vectors lie along the fiber axis. As a result, $\mathbf{k}_d = -\mathbf{k}_i$ and the diffracted light propagates backward. Thus, as shown schematically in Figure 1.1, a fiber grating acts as a reflector for a specific wavelength of light for which the phase-matching condition is satisfied. In terms of the angles appearing in Eq. (1.1.1), $\theta_i = \pi/2$ and $\theta_r = -\pi/2$. If $m = 1$, the period of the grating is related to the vacuum wavelength as $\lambda = 2\bar{n}\Lambda$. This condition is known as the *Bragg condition*, and gratings satisfying it are referred to as *Bragg gratings*. Physically, the Bragg condition ensures that weak reflections occurring throughout the grating add up in phase to produce a strong reflection at the input end. For a fiber grating reflecting light in the wavelength region near 1.5 μm, the grating period $\Lambda \approx 0.5$ μm.

Bragg gratings inside optical fibers were first formed in 1978 by irradiating a germanium-doped silica fiber for a few minutes with an intense argon-ion laser beam [3]. The grating period was fixed by the argon-ion laser wavelength, and the grating reflected light only within a narrow region around that wavelength. It was realized that the 4% reflection occurring at the two fiber–air interfaces created a standing-wave pattern such that more of the laser light was absorbed in the bright regions. As a result, the glass structure changed in such a way that the refractive index increased permanently in the bright regions. Although this phenomenon attracted some attention during the next 10 years [4]–[16], it was not until 1989 that fiber gratings became a topic of intense investigation, fueled partly by the observation of second-harmonic generation in photosensitive fibers. The impetus for this resurgence of interest was provided by a 1989 paper in which a side-exposed holographic technique was used to make fiber gratings with controllable period [17].

Because of its relevance to fiber-optic communication systems, the holographic technique was quickly adopted to produce fiber gratings in the wavelength region near 1.55 μm [18]. Considerable work was done during the early 1990s to understand the physical mechanism behind photosensitivity of fibers and to develop techniques that were capable of making large changes in the refractive index [19]–[47]. By 1995, fiber gratings were available commercially, and by 1997 they became a standard component of lightwave technology. Soon after, several books devoted entirely to fiber gratings appeared, focusing on applications related to fiber sensors and fiber-optic communication systems [48]–[50].

1.1.2 Photosensitivity

There is considerable evidence that the photosensitivity of optical fibers is due to defect formation inside the core of Ge-doped silica (SiO_2) fibers [29]–[31]. In practice, the core of a silica fiber is often doped with germania (GeO_2) to increase its refractive index and introduce an index step at the core-cladding interface. The Ge concentration is typically 3–5% but may exceed 15% in some cases.

The presence of Ge atoms in the fiber core leads to formation of oxygen-deficient bonds (such as Si–Ge, Si–Si, and Ge–Ge bonds), which act as defects in the silica matrix [48]. The most common defect is the GeO defect. It forms a defect band with an energy gap of about 5 eV (energy required to break the bond). Single-photon absorption of 244-nm radiation from an excimer laser (or two-photon absorption of 488-nm light from an argon-ion laser) breaks these defect bonds and creates GeE$'$ centers. Extra electrons associated with GeE$'$ centers are free to move within the glass matrix until they are trapped at hole-defect sites to form the color centers known as Ge(1) and Ge(2). Such modifications in the glass structure change the absorption spectrum $\alpha(\omega)$. However, changes in the absorption also affect the refractive index since $\Delta\alpha$ and Δn are related through the Kramers–Kronig relation [51]:

$$\Delta n(\omega') = \frac{c}{\pi} \int_0^\infty \frac{\Delta\alpha(\omega)d\omega}{\omega^2 - \omega'^2}. \tag{1.1.3}$$

Even though absorption modifications occur mainly in the ultraviolet region, the refractive index can change even in the visible or infrared region. Moreover, as index changes occur only in the regions of fiber core where the ultraviolet light is absorbed, a periodic intensity pattern is transformed into an index grating. Typically, index change Δn is $\sim 10^{-4}$ in the 1.3- to 1.6-μm wavelength range but can exceed 0.001 in fibers with high Ge concentration [34].

The presence of GeO defects is crucial for photosensitivity to occur in optical fibers. However, standard telecommunication fibers rarely have more than 3% of Ge atoms in their core, resulting in relatively small index changes. The use of other dopants, such as phosphorus, boron, and aluminum, can enhance the photosensitivity (and the amount of index change) to some extent, but these dopants also tend to increase fiber losses. It was discovered in the early 1990s that the amount of index change induced by ultraviolet absorption can be enhanced by two orders of magnitude ($\Delta n > 0.01$) by soaking the fiber in hydrogen gas at high pressures (200 atm) and room temperature [39]. The density of Ge–Si oxygen-deficient bonds increases in hydrogen-soaked fibers because hydrogen can recombine with oxygen atoms. Once hydrogenated, the fiber needs to be stored at low temperature to maintain its photosensitivity. However, gratings made in such fibers remain intact over relatively long periods of time, if they are stabilized using a suitable annealing technique [52]–[56]. Hydrogen soaking is commonly used for making fiber gratings.

Because of the stability issue associated with hydrogen soaking, a technique, known as ultraviolet (UV) hypersensitization, has been employed in recent years [57]–[59]. An alternative method, known as *OH flooding*, is also used for this purpose. In this approach [60], the hydrogen-soaked fiber is heated rapidly to a temperature near 1000°C before it is exposed to UV radiation. The resulting out-gassing of hydrogen creates a flood of OH ions and leads to a considerable increase in the fiber photosensitivity. A comparative study of different techniques revealed that the UV-induced index changes were indeed more stable in the hypersensitized and OH-flooded fibers [61]. It should be stressed that understanding of the exact physical mechanism behind photosensitivity is far from complete, and more than one mechanism may be involved [57]. Localized heating can also affect the formation of a grating. For instance, damage tracks were seen in fibers with a strong grating (index change >0.001) when the grating was examined under an optical microscope [34]; these tracks were due to localized heating to several thousand degrees of the core region, where ultraviolet light was most strongly absorbed. At such high temperatures the local structure of amorphous silica can change considerably because of melting.

1.2 Fabrication Techniques

Fiber gratings can be made by using several techniques, each having its own merits [48]–[50]. This section discusses briefly four major techniques, used commonly for making fiber gratings: the single-beam internal technique, the dual-beam holographic technique, the phase-mask technique, and the point-by-point fabrication technique. The use of ultrashort optical pulses for grating fabrication is covered in the last subsection.

1.2.1 Single-Beam Internal Technique

In this technique, used in the original 1978 experiment [3], a single laser beam, often obtained from an argon-ion laser operating in a single mode near 488 nm, is launched into a germanium-doped silica fiber. The light reflected from the near end of the fiber is then monitored. The reflectivity is initially about 4%, as expected for a fiber–air interface. However, it gradually begins to increase with time and can exceed 90% after a few minutes when the Bragg grating is completely formed [5]. Figure 1.2 shows