Chapter 9

BRAGG GRATINGS IN OPTICAL FIBERS

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1. INTRODUCTION

1.1. Fiber Bragg Gratings

Optical fiber networks have been developed to the point where they are now synonymous with modern telecommunications and optical sensing. A major drawback to their evolution has been the reliance on bulk optics for conditioning and controlling the guided light beam, which requires the use of high quality bulk-optic components and places stringent tolerance on optical alignment—thus making conceptually simple systems complicated and expensive in practice. Replacing a bulk-optic mirror or beam splitter with a fiber equivalent can dramatically increase system stability and portability, while reducing overall size. The most successful fiberized technology to date is reflected in the optical fiber laser and amplifier and fused tapered coupler. The significant discovery of photosensitivity in optical fibers led to the development of a new class of in-fiber components called *fiber Bragg grating*. Photosensitivity refers to a permanent change in the index of refraction of the fiber core when exposed to light with characteristic wavelength and intensity that depend on the core material. The fiber Bragg grating can perform many primary functions, such as reflection and filtering, in a highly efficient low-loss manner. This versatility has stimulated a number of significant innovations [1–3].

For a conventional fiber Bragg grating, the periodicity of the index modulation has a physical spacing that is one-half of the wavelength of the light propagating in the waveguide, and it is phase matching between the grating planes and the incident light that results in coherent back-reflection. Reflectivities approaching 100% are possible, with a grating bandwidth tailored typically from 0.1 nm to in excess of 100 nm. These characteristics make Bragg gratings suitable for telecommunications and sensing [1]. For example, fiber lasers that produce light in telecommunications windows utilize Bragg gratings to form the laser cavity mirrors, which realize an efficient and inherently stable source. Moreover, the ability of gratings with nonuniform periodicity to compress or expand pulses is particularly important to high-bit-rate long-haul communication systems. Grating-based dispersion compensation of 10-Gbps transmission systems over several hundred kilometers has been demonstrated. Furthermore, the Bragg grating meets the demands of dense wavelength-division multiplexing, which requires narrow-band, wavelength-selective components, offering very high extinction between information channels. There are numerous applications that exist for low-loss fiber-optic filters, for example, ASE noise suppression in amplified systems, pump recycling in fiber amplifiers, and soliton pulse control. The ability to selectively couple light between core and cladding radiation modes may be employed in fiber amplifiers to selectively outcouple unwanted wavelengths and give uniform spectral gain. Additionally, the wavelength-selective properties of gratings have been used to generate true time delays in microwave phased-array antenna systems.

The wavelength-dependent grating reflectivity leads to a wavelength–strain responsivity of $\sim$1 pm/nε, at 1.5 μm, with a wavelength shift of 15 pm/°C for temperature excursions. Tracking the Bragg wavelength gives information with regard to the magnitude of an external perturbation. This functionality approaches the ideal goal of optical fiber sensors: to have an intrinsic in-line, fiber-core structure that offers an absolute readout mechanism. The reliable detection of sensor signals is critical, and spectrally encoded information is potentially the simplest approach that offers simple decoding. The grating may also be used as reflective markes tor map out lengths of optical fiber for optical time-domain measurements. Importantly, the basic instrumentation applicable to conventional optical fiber sensor arrays may also incorporate grating sensors, which permits the combination of both sensor types. Bragg gratings have been used to measure dynamic strain in aerospace applications and as temperature sensors for medical applications. They also operate well in hostile environments such as high pressure, borehole-drilling applications.

1.2. Photosensitivity Background

Hill et al. [4, 5] first noticed photosensitivity to light at 488 nm in germanosilicate optical fibers. The growth with laser power was associated to a two-photon process [6], and thus a connection with the well-known 248-nm absorption band was made. A transverse writing method was later used to photoimprint Bragg gratings at a direct excitation wavelength of 240 nm [7]. The absorption band centered on this excitation has been related to defect centers in germanosilicate glass [8, 9]. Irradiation with a wavelength that coincides with this band was shown to result in bleaching, while creating other absorption bands that lead to a refractive-index change that is described via the Kramers–Kronig relationship [10]. In 1993, Lemaire et al. [11] showed that significantly larger index changes could be achieved by "hydrogen loading" the glass before exposure and, in some cases, without variation of the 240-nm absorption band. The latest experimental findings indicate the formation of spectral changes below 240 nm, and that 193-nm excitation of non-hydrogen-loaded low germanium content fiber can result in high index changes that are commensurate with the fiber core-cladding refractive-index difference [12]. It appears that photosensitivity at 193 nm obeys one-photon dynamics in high germanium content fiber and two-photon dynamics in low germanium content fiber. A two-photon process also has been observed in germanosilicate glass for various UV wavelengths [13]. The current consensus of opinion is that photosensitivity is initiated through the formation of color centers [14] that give way to compaction of the UV-irradiated glass [15, 16]. The phenomenon of photosensitivity arguably has resulted in one of the most important in-fiber components called the fiber Bragg grating [1].

2. PHOTOSENSITIVITY

2.1. Photosensitivity in Silicon-Based Optical Fibers

Early studies on photosensitivity and grating growth pinpointed the essential requirement that germanium be present [17]. However, there are now numerous examples in the literature of photosensitivity in a wide range of fibers, many of which do not contain germanium as a dopant. Fibers doped with europium [18], cerium [19], and erbium:germanium [20] show varying degrees of sensitivity in a silica host optical fiber. One fiber doping that produces large index modulations (on the order of 10^{-3}) is germanium–boron codoping [21]. Photosensitivity also has been observed in a fluorozirconate fiber [22] doped with cerium:erbium, where Bragg gratings were inscribed using 246-nm radiation. From a practical point of view, the most interesting photosensitive fibers are germanium core-doped, because they are used extensively in both the telecommunications industry and optical sensor applications.

When photosensitivity was thought to occur only in germanium-doped fiber, it was believed that the germanium oxygen vacancy defects, such as a twofold coordinated neutral germanium atom ($\mathrm{O{-}Ge{-}O}$ or Ge_2^0 center) or $\mathrm{Ge{-}Si}$ or $\mathrm{Ge{-}Ge}$ (the so-called *wrong bonds*) were responsible for the photoinduced index changes. However, demonstration of photosensitivity in most types of fiber made it apparent that photosensitivity is a function of various mechanisms (photochemical, photomechanical, thermochemical), and the relative contribution is fiber dependent, in addition to intensity and wavelength dependent. Several models proposed to describe the photoinduced refractive-index changes in germanium-doped fiber share the common element of germanium oxygen vacancy defects as precursors that are responsible for the photoinduced index changes. During the high-temperature gas-phase oxidation process of the modified chemical-vapor deposition (MCVD) technique, $\mathrm{GeO_2}$ dissociates to the GeO molecule (in other words, the Ge^{2+} center) due to its higher stability at elevated temperatures. This species, when incorporated into the glass, can manifest itself in the form of oxygen vacancy $\mathrm{Ge{-}Si}$ and $\mathrm{Ge{-}Ge}$ "wrong bonds." Regardless of which particular defect causes an oxygen-deficient matrix in the glass, it is linked to the 240–250-nm absorption band (peaking at 242 nm) and its centers are known as germanium oxygen-deficient centers (GODCs).

The growth dynamics of the Bragg gratings as they are exposed to UV radiation give an important insight into the photosensitivity of fibers. We can distinguish three distinct dynamical regimes known as Type I, Type IIA, and Type II [23]. The key differences are highlighted in Table I. It is almost certain that the mechanisms responsible for Types I, IIA, and II are different. The physical properties of these grating types also may be inferred through their growth dynamics and by measurement of thermally induced decay. The accelerated decay is different for each grating type: with Type I is the least stable and Type II is the most stable with temperature; Type IIA falls in between. This is not surprising given that Type I is related to local electronic defects, Type IIA is related to compaction, and Type II is related to fusion of the glass matrix. Niay et al. [24] asserted that the growth dynamics of UV-written Bragg

Table I. Key Differences between Types I, IIA, and II Bragg Gratings

Grating type	Cumulative fluence (J/cm^2)	Typical pulse energies (mJ/cm^2)	Writting conditions cw	Writting conditions Pulsed	Observations
Type I	Up to 500	100	√	√	Applicable to self-organized and externally written gratings $\Delta n > 0$ Associated with defects and density changes in glass matrix
Type IIA	>500	100	√	√	Applicable to externally written gratings $\Delta n > 0$ Associated with compaction of the glass matrix
Type II	Not applicable	1000	X	√	Applicable to externally written gratings $\Delta n > 0$ Associated with fusion of the glass matrix