Chapter I : Introduction

1.1 Introduction

Optical fibers have revolutionized telecommunication due to its properties such as low transmission loss (less than 1dB/km), high optical damage threshold, and low optical nonlinearity, which have enabled long distance communication to become a reality. The next stage in the field of communication is the mass delivery of integrated services, such as home banking, shopping, internet services and entertainment which demand highly. Architectures for future networks need to exploit technologies, which have the potential of driving down cost to make services economically viable. This then is a motivation for alternative technology exploration which gave birth to wavelength division multiplexing (WDM). An important and integral component of WDM is the fiber Bragg grating (FBG), which is in fact the enabling technology for WDM.

FBG, an in fiber filter solution, offers a good alternative to bulk optic filters. The technological advance made in the field of photosensitive optical fibers contributed to an increasing number of fiber devices based on this technology such as FBG. Since they were first discovered in 1978 [1], FBGs have undergone intensive development as indicated by the large number literature, and at conferences worldwide recently. FBGs were first used on a large-scale commercial basis about 6 years ago as laser pump stabilizers for erbium-doped fiber amplifiers (EDFAs) and as filters for some multiplexers and demultiplexers. Many other applications have been demonstrated and are still under development including, channel add-drop modules, bandpass and broad band blocking filters, gain equalizing and gain flattening for

EDFAs, laser diode wavelength locking, dispersion compensation, single frequency fiber laser sources, Raman amplifier and high power Raman pump sources [2].

There are competing technologies for most of these applications. FBGs have an advantage of being an in-fiber component, which does not require a transition out of and back into a fiber which will cause additional loss. FBGs are very small, rugged and can be made reliable and stable for long-term applications. They also can produce excellent filter profiles with relatively steep slopes for multiplexing applications. Problems with FBGs include possible out-of-band reflections, cladding mode losses, temperature sensitivity, and spurious reflecting elements, which can create return loss problems in some applications. For a large channel count the problem of connecting a large number of FBG elements in a single component can become cumbersome. Many of these problems are being overcome with time. Cost reduction is also an important development that must continue in order to make FBG's more competitive.

FBGs have been commercially available since early 1995, and in that short time, four FBG types have evolved. First is a simple reflective type of FBG. These are single fiber grating functioning as wavelength-selective retroreflectors to replace mirrors and filters. A wide range of Bragg wavelength and performance specifications are available in the market. Second is a broadband type of FBG, which can be designed to operate over a broad Bragg wavelength range with bandwidths of several nanometers. This performance is achieved through grating design or chirping and apodization. Broadband FBGs are slated for use in reflective dispersion compensator modules (chirped) and gratings-based WDM multiplexers and add/drop modules (chirped or unchirped). Third is a mode coupling type of FBG, that can be designed to either promote or suppress mode coupling of Bragg wavelengths to fiber radiation or cladding modes. For example, blazed gratings can be designed to reflect at an angle to excite higher order modes or to create wavelength-selective fixed attenuator elements by directing light to the mode-stripping cladding portion of the fiber where light is absorbed and signals attenuated. The last is a band-rejection type of FBGs. Broadband FBG designs can be combined with mode-coupling grating techniques described above to yield broadband wavelength selective rejection filters. These broadband rejection elements are ideal for system test channel-blocking filters, EDFA gain-flattening filters and fixed attenuator elements.

1.2 Brief history of fiber Bragg gratings

The formation of permanent gratings in an optical fiber were first reported by Ken Hill and co-workers in 1978 at the Canadian Communication Research Center (CRC), Ottawa, Ont., Canada [1]. They launched intense Argon-ion laser radiation into a germanium-doped fiber and observed that after several minutes an increase in the reflected light intensity occurred which grew until almost all the light was reflected from the fiber. Spectral measurement, done indirectly by strain and temperature tuning of the fiber grating, confirmed that a very narrowband Bragg grating filter had been formed over the entire 1 m length of fiber. This achievement, subsequently called "*Hill gratings*," was an outgrowth of research on the nonlinear properties of germania-doped silica fiber. It established a previously unknown photosensitivity of germania fiber, which prompted other inquires, several years later, into the cause of the fiber photo-induced refractivity and its dependence on the wavelength of the light, which was used to form the gratings.

In 1981, Lam and Garside [3] showed that the grating strength increased as the square of the light intensity and identified the process behind grating formation in the experiment of Hill *et al.* [1] as a two-photon process. In the original experiment, laser radiation at 488nm was reflected from the fiber end producing a standing wave pattern that forms the grating. Several years later, a single photon at half this wavelength, namely at 244nm in the deep ultraviolet, proved to be more effective. In 1989, Gerald Meltz *et al.* [4] showed that this radiation could be used to form gratings that would reflect any wavelength by illuminating the fiber through the side of the cladding with two intersecting beams of UV light. The scheme provided the much-needed degree of freedom to shift the Bragg condition to longer and more useful wavelength, predominantly dependent on the angle between the interfering beams. This principle was extended to fabricate FBGs at 1530nm, a wavelength of interest of telecommunications, also allowing the demonstration of the first fiber laser operating from the reflection of the photosensitive fiber grating [5].

The UV-induced index change in untreated optical fibers was $\sim 10^{-4}$. Since then, several developments have taken place that have pushed the index change in optical fibers up a hundredfold, making it possible to create efficient reflectors only a hundreds of a wavelength long. In 1991, Meltz and Morey [6] reported enhanced photosensitivity for the production of fiber gratings due to hydrogen loading the fibers. Later, Lemaire and co workers [7] showed that the loading of optical fiber with molecular hydrogen photosensitized even standard telecommunication fiber to the extent that FBGs with very large refractive index modulation could be written.

FBGs written by excimer laser were first reported by Atkins *et al* [8] and it was later demonstrated by Archamboult et al [9] that controlled damage gratings could be produced using a side writing interferometer. A major step toward easier inscription of FBGs was made possible by the application of the phase mask as a component of interferometer. The use of a phase mask for side-writing the FBG was originally introduced by Hill and Anderson, respectively, in 1993 [10], [11].

1.3 Photosensitivity

When ultraviolet light radiates an optical fiber, the refractive index of the fiber is changed permanently; the effect is termed photosensitivity. Initially, photosensitivity was thought to be a phenomenon associated only with germanium-doped optical fibers. Subsequently, it has been observed in a wide variety of different fibers, many of which did not contain germanium as a dopant. Nevertheless, optical fiber having a germanium-doped core remains the most important material for the fabrication of devices. The photosensitive in single mode fibers seems to be due to the ionization of the oxygen vacancy defects in the UV wavelength range and to subsequence structural modifications. Different models are proposed to explain the laser induced index changes. Creation of GeE' hole centers and the trapping of the released electrons at Ge(1) and Ge(2) sites are assumed [12]. Another model is based on a densification effect due to structural rearrangements [13], [14]. Nevertheless, the origin of the photosensitivity in germanium-doped fibers is still in question.

The photosensitivity can be enhanced by increasing the colour center concentration. It can be produced by increasing the germanium concentration. The index change in standard fiber with a germanium concentration of typically 3 to 5% are of the order of 3×10^{-5} [15]. Williams et al. [15] reported the fabrication of a special fiber with an increased germanium content of 20% leading to index change of 5×10^{-4}. The increased germanium content reduces concomitantly the mode field diameters, which limits the application of such fibers in telecommunication networks, because of induced loss at the fiber splices. The mode field diameter can be adapted by co-doping the fiber core with boron, which increases the photosensitivity. FBGs written in such fibers have been obtained with an index change of 7×10^{-4} [16].

The photosensitivity can also be enhanced by hydrogen loading the fiber e.g. in a high pressure (>200 atmospheres) and low temperature (room temperature) diffusion process. Hydrogen is used because it effectively creates defect formation in germanium-doped glass. The refractive index change obtained can exceed 10^{-2}, which is above the core-cladding index difference of typical fibers [17]. The hydrogen loading techniques can be applied locally leaving the rest of the fiber unaffected. Any germanium-doped fiber can be photosensitized this way, even when it is initially of low photosensitivity. The use of boron as a co-dopant in germanosilicate fibers and hydrogenation are the most well-established photosensitization methods.

1.4 Content of dissertation

Considering the limited apparatus in the laboratory – uniform phase mask, Gaussian beam ultra violet (UV) laser and mounts – the FBG would be limited to uniform gratings of short period (<600nm) nature.

Chapter II gives the theoretical background of the FBG. The optical properties of the short period FBG are given. Coupled mode theory is used to formulate the basic equations for analyzing the properties of uniform gratings when coupling occurs between two counter propagation modes. The analysis is extended to two modes coupling in non-uniform grating such as apodised and chirped gratings in the following section.

Chapter III describes the fabrication of the uniform short period FBG. The experimental set-up, alignment and tools used in the set-up such as fiber, phase mask and UV laser source are explained in detail. This chapter also explains the growth behaviors and features like cladding mode and side-lobes of the fabricated FBG.

Chapter IV gives the detailed spectral characterization of fabricated FBGs. The measurements of temperature dependence of the bare and packaged FBG spectra are also presented. The FBG reliability is also discussed in this chapter.

The application of FBGs in gain-clamped EDFA and fiber laser is investigated in chapter V. An FBG is used to provide optical feedback in the cavity of EDFA system. The effect of the pump power, input signal power and optical feedback power attenuation on the EDFA performance parameters such as output signal power, signal gain and noise figure are investigated in section 5.2. A fiber laser with different FBG's as an optical feedback element is studied and compared in the following section. The laser characteristic such as threshold pump power, slope efficiency etc are investigated. Laser tuning is also verified in this section.

The summary of this thesis is found in Chapter VI. This chapter also concludes with some discussion and suggestions for future work.

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