UNIVERSITI PUTRA MALAYSIA

EFFECTS OF SEGMENTATION AND STEP SAMPLING ON APODIZED FIBER BRAGG GRATING

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DEDICATION

To The Martyrs of Palestine

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Practical implementation of apodized fiber Bragg grating results in approximation to the apodization profile. In this study, these profiles are simulated by sampling and segmentation. Segmenting an ideal profile is basically producing its corresponding piecewise linear profile. The number of segments varies with the error value, which is defined as the maximum absolute difference between the segmented profile and the ideal one. The relationship between the error and the number of segments is found to be one to many. To study the process normal and DWDM gratings have been considered. The quality of the fiber Bragg gratings was investigated through the maximum reflectivity, the SLSR, and the bandwidth of the normal gratings, the insertion loss, the bandwidth, and the crosstalk parameters for the DWDM gratings.

Some of the results are unexpected. Segmentation enhances the quality of the gratings for some error values. For example, side lobe suppression ratio for normal grating apodized with segmented profile is improved by around 5.8dB at error of 0.015 compared to the grating apodized with smooth function. An enhancement of 0.5% on the

maximum reflectivity is also achieved for these normal gratings. For DWDM gratings the insertion loss is decreased by an amount of 0.002dB and the adjacent crosstalk is improved by an amount of around 2.5dB for some approximated Cosine apodization profile.

The study was also done to investigate the sampling effect. Sampling rate was varied for a fixed value of the maximum error. The study showed a good grating quality over a wide range of sampling. This would have an impact of relaxing the practical implementation of such process. In order to explain the results obtained, a criteria was formulated. This is based on the integration of error function. This criterion was instrumental in explaining the results.

Abstak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sians

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Pelaksanaan praktik bagi "apodized fiber Bragg grating" mengakibatkan penganggaran pada profil "apodization". Dalam kajian ini, kami menganggarkan profil-profil ini dalam pensegmenan. Pembahagian untuk profil ideal asasnya adalah mengeluarkan sempadan profil "piecewise linear". Bilangan bahagian-bahagian adalah berbeza dengan ralat kadar, yang mana telah di jelaskan sebagai perbezaan mutlak yang maksimum diantara profil yang dibahagikan dan profil ideal. Perhubungan antara ralat dan bilangan segmen telah banyak berlaku. Untuk mengkaji proses tersebut kami telah mengambil kira grating normal dan DWDM. Kualiti bagi "fiber Bragg gratings" telah dikaji melalui pemantulan maksimum, "SLSR", dan "bandwidth" pada grating normal, "insertion loss", "bandwidth" dan parameter "crosstalk" untuk grating DWDM.

Keputusannya tidak dapat diduga. Pembahagian telah mempertingkatkan kualiti bagi grating-grating untuk beberapa kadar ralat. Sebagai contoh, nisbah "side lobe suppression" untuk grating normal "apodized" dengan profil "segmented" telah di

tingkatkan lebih kurang 5.8dB pada ralat 0.015 berbanding dengan grating apodized dengan fungsi lancar. Satu peningkatan pada 0.05% ke atas pemantulan maksimum juga telah tercapai untuk grating-grating normal ini. Bagi grating DWDM "insertion loss"nya telah dikurangkan lebih kurang 0.002dB dan "adjacent crosstalk" telah ditingkatkan pada kadar 2.5dB.

Kajian telah dijalankan untuk mengkaji kesan "sampling". Kadar "sampling" adalah berbeza pada kadar tetap untuk ralat maksimum. Kajian ini menunjukkan kualiti tetap ke atas pelbagai jenis "sampling". Ini akan mengendurkan kesan proses perlaksanaan. Untuk menerangkan keputusan yang telah dicapai, satu kriteria telah di formulakan. Ini adalah berdasarkan kepada persepaduan fungsi ralat. Kriteria ini telah menjadi faktor dalam menerangkan rumusan kajian.

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LIST OF ABBREVIATIONS

AXT	Adjacent crosstalk
CRC	Communication Research Center
CW	Continuous Wave
DFB	Distributed Feedback Grating
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
EMI	Electromagnetic Interference
FBG	Fiber Bragg Grating
FBGs	Fiber Bragg Gratings
FWHM	Full Wave Half Maximum
IL	Insertion Loss
ITU	International Telecommunication Union
MPF	Multiple Printing of in-Fiber Grating
NAXT	None Adjacent crosstalk
OEC	Optical to Electrical Conversion
R_{max}	Maximum Reflectivity
SL	Side lobe
SLSR	Side lobe Suppression Ratio
SMF	Single Mode Fiber
SNR	Signal to Noise Ratio
UV	Ultra Violet
WDM	Wavelength Division Multiplexing

CHAPTER ONE

INTRODUCTION

The usage of optical fiber has revolutionized the telecommunication sector. It can transfer the information over very long distances because of its distinguished properties such as the small attenuations at certain wavelengths. Nowadays most of the telecommunication companies are using fiber links, and the fiber market is still increasing. It is believed to be the best media for transferring data in the future.

Wide transmission bandwidth is needed to cover the large demand for telecommunication and the increasing number of data services offered. Most of the services offered are data type services, like the Internet. Thus, the transmission volume of data type information is increasing faster than that of the voice. However, both of them need a high bandwidth transmission media. Optical fiber covers this gap with Wavelength Division Multiplexing (WDM) or Dense WDM (DWDM) transmission techniques. With these methods, four to eight channels (WDM) or more (DWDM) are sent on the same Single Mode Fiber (SMF) that has already been installed. This technique increases the optical fiber importance in telecommunication because it can provide us with a large bandwidth at competitive cost compared to that of other transmission media such as the copper cables, radio links, satellite links, or any other medium. Moreover, fiber has more advantages such as electromagnetic immunity, high temperature withstanding, lightness, lower costs for long distances, and more security [3,31]. DWDM systems are now being commercially deployed for point-to-point communication links. Recent studies are concentrating to make the DWDM systems work in a network environment.

The discovery of optical fiber photosensitivity opens the way to the DWDM system to become viable. The technology of photosensitive fiber is based on an in-fiber optical filter called Fiber Bragg Grating (FBG). From this basic component, a large number of devices are now available and providing the DWDM system with the basic functions like the multiplexing and channel selection.

1.1 Historical Prospective of FBG

The technological advances related to fiber photosensitivity is relatively recent, and the number of optical devices that depend on these advances in the market is increasing. Wavelength division multiplexers, add/drop multiplexers, and other devices are now available in the market. This makes the DWDM network system easier to be achieved. And they will finally provide with other devices the routing for the DWDM system at the end of the way.

The optical fiber photosensitivity was discovered in 1978 by Hill and Kawasaki [8,14] at the Communication Research Center (CRC) in Canada. They were doing an experiment to study the non-linearity of a specially designed fiber heavily doped with germanium. In this experiment they launched into the core of the fiber a 488 nm intense visible light. And the transmitted and reflected light was measured during the exposure time. They found out that the transmitted light was attenuated. During exposure, the reflected light intensity was increasing significantly with time. After a specific time all the incident light was totally reflected. The spectral measurements confirmed that this reflection was occurring because of the photo-induced change in the refractive index of the fiber core. This experiment makes an important phenomenon called photosensitivity to be observed for this type of fiber. The increasing interest of researchers in the photosensitivity of optical fiber from then on, led to the production of many photosensitive devices.

The launched light at one terminal of the fiber core interfered with the Fresnel reflected beam from the other terminal of the fiber, to produce a standing wave intensity beam. This standing beam altered the refractive index of the core in this photosensitive fiber at the high intensity points permanently. Thus, the refractive index takes the shape of the intensity of the standing beam, which is a periodic change with the length of the fiber. This refractive index perturbation couple the forward and backward propagating light beams. The reflected beam enhanced the strength of the back-reflected beam, which increases the intensity of the interference pattern. This process continues until the refractive index of the core reaches saturation level.

These first experiments achieved a 90% permanent reflectivity of the incident beam. And the change in the modulated index (Δn) was approximated to be around (10^{-5}) to (10^{-6}). The bandwidth was measured, by stretching and temperature tuning, to be 200 MHz [11]. The characteristics of this grating were very useful in communication, but the major limitation is that its function is only valid at the visible part of the spectrum around the writing wavelength.

Since then, researchers started to be very interested in the photosensitivity of that special type of fiber presented by Bell Northern Research center which has a small diameter and is heavily doped with germanium. Lam and Garside [16] showed that the magnitude of the refractive index change; depend on the square of the writing power at the argon ion wavelength. This is called the two-photon process. The international interest was not that much at that time because they believed that this property is present only in this special design of fiber. In 1987 Stone [25] proved that the photosensitivity is not a characteristic of only that type of fiber when he demonstrated the same effect on the GeO_2-doped silica fiber. This ensures that the photosensitivity is a property of many types of fiber. This has ignited worldwide interest in making useful optical fiber devices such as selective spectral filters, DWDM multiplexers, add/drop multiplexers, and other optical devices.

In 1989, Meltz et al. [21] demonstrated the side writing technique. This phenomenon proved to be practical in telecommunication systems. This was done at the United Technology Research Center, and his writing method is called the holographic technique. He found out that the refractive index of the germanium doped fiber core is strongly affected by the side exposure to the single-photon, UV light with a power of 5 eV. Exposing the side of the fiber to interfering beams with 244 nm will produce a modulation in the refractive index of the core. By changing the angle between the interfering beams, the period of interference will be changed accordingly. This makes the reflected beam from this grating to be possible at the (1300-1500 nm) range of wavelength. Even though the phenomenon is still related to the absorption of light in the

Ultra Violet (UV) range, gratings can be fabricated to any wavelength, which makes the grating more practical in the telecommunication and sensing fields.

Afterward, Meltz method was developed to get a modulation index up to (2×10^{-3}) [11]. Further research make it possible to achieve modulation index same as the difference between the refractive index of the core and the cladding. One of the important advantages of the single-photon over the two-photon process is the power needed for each one, to get the same value of modulation index. The two-photon process needs around $1GJ/cm^2$ of influence level for the modulation index to saturate. While the single photon process takes only $1KJ/cm^2$ for the same index change, which is one million times less. Table 1.1 shows some of the major differences between the two methods mentioned above [8,9].

Table 1.1: Differences between single and two photon FBG fabrication techniques

Property	Two photon process	Single photon process
Exposure	Internally	Externally
Grating length	Along the length of he fiber	Same as the interference length
Reflection wavelength	240-250 nm	240-1600 nm
Influence level	$\approx(1GJ/cm^2)$ to saturate	$\approx(1KJ/cm^2)$to saturate
Popularity	Not used for commercial production	Used for fabrication in industry for mass production

The most important parameters that affect the modulation index is shown to be the writing beam wavelength, intensity, the exposure time, the composition of the fiber under exposure, and any other pre-processing that may be done to the fiber, like hydrogenation. The laser sources used in fabrication of the Fiber Bragg Gratings (FBGs) are KrF and ArF excimer lasers, which are UV laser sources operating at 248, and 193 respectively. These lasers generate pulses of laser light each with 1020 ns duration at a frequency of 10's of Hz. A typical example shows that exposing the germanium doped single mode fiber to a UV laser for several minutes with irradiation intensity of $100-500mJ/cm^2$, will produce a refractive index change of magnitude $\Delta n = 10^{-5} - 10^{-4}$ [30,9].

Lamaire et al. [17] showed that optical fiber hydrogenation photosensitize even the standard telecommunication fiber. Loading the fiber with hydrogen before fabrication, produce a very sensitive fiber to the UV light. So gratings with hundred time's higher modulation index were achieved $(\Delta n = 10^{-2})$. This makes the grating a basic component in many linear and non-linear optical devices.

Phase mask was proposed by Hill et al. [12] in 1993 to be used for the fabrication of fiber Bragg gratings (FBGs). The phase mask is a surface relief grating etched in silica plate of glass. It diffracts the UV light beam into several orders, (0, +1, -1, +2, -2….) Depending on its period, the angle of the orders can be controlled, and the efficiency of these orders depends on the mark-space ratio and the etch depth. Special phase masks that have high diffraction efficiency for the plus and minus first orders, and minimum efficiency for the rest of the orders, are used in the fabrication. Exposing this phase mask to the designed UV wavelength will split the beam into the plus and minus orders, which will interfere, just near the opposite side of the phase mask. Placing the fiber a distance close to the diameter of the fiber to the phase mask, will produce a Bragg grating with a period similar to that of the interference pattern which is half the grating pitch period of the phase mask. This technique does not add any improvement on the magnitude of the modulation index, but it relaxes both the high sensitive issue of alignment process needed for the holographic technique, and the stability and quality conditions needed for the laser source. So it has become the most popular technique especially for the mass production of the fiber gratings.

1.2 Fiber Bragg Grating Applications in Telecommunications

The increasing demand for network bandwidth is principally due to the growth of the data traffic. WDM and DWDM are transmission techniques that provide the networks with the needed bandwidth and speed. These techniques multiplex the data into different wavelength channels, with a constant spacing between them. Using the DWDM systems as a network solution requires many functions to be done in the optical domain, because the Optical to Electrical Conversion (OEC) incurs losses and is a costly option. Devices that provide some of the network functions as DWDM Multiplexers, add/drop Multiplexers and the cross connect may be realized by fiber Bragg gratings [16].

Fiber Bragg gratings are basic components used in many devices because they are in-fiber components and they have unique filtering characteristics. They are used in wavelength-stabilized lasers, fiber lasers, remote pump amplifiers, Raman amplifiers, phase conjugators, wavelength converters, wavelength division multiplexers, add/drop multiplexers, dispersion compensators, and gain equalizers [5,28].

Although the fiber Bragg grating is a band-stop and not a band pass filter, there are solutions to get the desired spectrum in the reflection or transmission of the gratings. Additional devices are required to achieve the desired functionality in the reflection spectrum, such as circulators and couplers. On the other hand, solutions like distributed feedback (DFB) gratings, Fabry-port interferometer, moiré resonator, and slide tap filters