Chapter VI: Summary and Conclusion

High reflectivity short period fiber Bragg gratings (FBGs) have been fabricated and its characteristics and performance were investigated in this study. The FBGs have a reflectivity ranging from 98 ~ 99.9%, bandwidth of 0.3 ~ 0.9 nm and center wavelength of 1552.5 ~ 1553.5 nm. The time taken for the FBGs to be written were within 10 to 30 minutes depending on the alignment. These characteristics were obtained using a experimental set up which consists of a 244nm continuous wave (CW) frequency doubled Argon ion laser, two circular lenses, a cylindrical lens and a phase mask. A high germania boron co-doped fiber was used to inscribe the FBG since it is designed to be intrinsically photosensitive and compatible with conventional telecommunication fibers. The germania provides the photosensitivity and boron both acts to depress the index back down and reduces the inscription time. The phase mask with ±1 order, which contains 36% of the UV intensity and 0 order containing 1% UV intensity is used in the experiment. The UV laser beam passing through the phase mask is diffracted to form a three-dimensional interference pattern, which induces a refractive index modulation in the core of the fiber used. The CW frequency doubled argon ion laser with beam diameter of 1.191mm and maximum output power of 100mW is used in the experiment. This laser has a high spatial and temporal coherence, which makes the inscription easier. However, this laser has mechanical disadvantages such as having a small beam diameter and power. The fabrication and alignment is easier if a high pump laser like the 248nm KrF excimer laser is used. It has a 10 times larger beam diameter and higher power than the argon ion laser.

Side-lobe is found on the short wavelength side of the fabricated FBGs. It arises due to a self-induced chirp in the grating period, which causes the resonant wavelength on either end of the grating to be smaller than the resonant wavelength of the central portion of the grating, setting up Fabry-Perot resonance. The self-induced chirp is caused by non-uniform index change due to the beam profile having a Gaussian distribution. The side-lobe can be eliminated using a double exposure [1], apodised phase mask [2] etc.

Besides this, a series of transmission dips also appear in the transmission spectrum of the fabricated FBG at the short wavelength side. A higher reflectivity FBG shows a more severe cladding mode disturbance. The cladding mode is caused by wave coupling between the guided fundamental and higher order modes within the cladding in the fiber. This phenomenon occurs due to asymmetry in the UV-induced index which is in turn caused by asymmetry of transverse absorption of UV light during writing. The cladding mode loss can be reduced by having a photosensitive cladding [3] and using a special fibers such as a depressed cladding fiber [4].

The fabricated FBGs are characterized using both fiber amplifier (broadband source) and tunable laser source (TLS, narrowband source) as the profile source. Scanning with a broadband probe source is very fast compared to narrowband source. This advantage makes broadband sources very suitable for use in real time monitoring. Because of the limited resolution of the OSA, the TLS is used when measuring the transmission dip of high reflectivity FBGs. By using the TLS, scanning of the source and the OSA are synchronized with an appropriate OSA slit width. The TLS probing method has shown a higher value of transmission dip, which is more accurate compared to the fiber amplifier.

The maximum reflectivity is usually calculated using the measured transmission dip T_d from the transmission spectrum by a formula given as

$$R = 1\text{-}10^{-T_d/10}.$$

The reflection peak from the reflection spectrum is not used to calculate reflectivity accurately since this method needs a calibration to be carried out. The 3.6% Fresnel reflection can be used to calibrate the reflected signal measured by OSA. However, the calibration proved to be unreliable since the losses are not stable. Nevertheless, the reflection spectrum still can be used to monitor the growth of gratings at early stages because it can easily detect a very weak Bragg reflection signals. Reflections just above the noise floor of the OSA are easily displayed with this spectrum. On the other hand, the transmission spectrum shows no change until the grating reflectivity exceeds the Fresnel reflection of 3 ~ 4%.

The wavelength shift induced by temperature variation in a bare FBG fabricated in the lab is also studied. Two different methods are used to subject the FBG to temperature variation, i.e. using an oven and using a Peltier heat pump. Both methods show that the wavelength has a linear response to temperature variation. The structure of the spectrum does not change with temperature. The thermal responses are the same for both methods, which is shown to be 0.010nm/°C. This wavelength shift is caused by thermal expansion and thermo-optic effects. The theoretical calculated value for thermal response is 0.012nm/°C. So, the experimental value is consistent with the theoretical calculated value. However, a slight discrepancy of 0.002nm/°C is observed, which is probably due to the applied temperature not being distributed uniformly in the bare FBG.

The fabricated FBGs give a center wavelength change of approximately 1nm for every change of 100°C. This is unacceptable for application in DWDM networks and other importance applications because the filter bandwidth itself may only be 0.3nm.We have tried to reduce this thermal response by packaging the fiber in three stages. The results show that the temperature response reduced from 0.0101 to 0.0093 after being packaged in a U-sharped crystal tube, reduced again to 0.0091 with the inclusion heat shrink tube. However, it increases to 0.0104 in the complete package after being locked inside a metal sleeve. It is concluded that this type of packaging method is only effective to prevent the FBG from breaking or damage from mechanical shock, but it cannot effectively isolate the thermal response of the FBG.

The utilization of the FBG in a gain-clamped EDFA system is studied since EDFA is one of the critical devices in a WDM system. The FBG with a reflectivity of approximately 70% is used to provide an optical feedback in the cavity. The effect of the pump power, input signal power and optical feedback power attenuation on the amplifier characteristics are studied. The experiments are carried out by comparing the amplifier performance for configurations with and without FBG. The configuration with FBG has shown that output power and gain increase with pump power at low pump powers before it is clamped in the saturated regions. This clamping phenomenon happens due to the onset of laser oscillation so that a constant average population inversion is maintained. However, the open system has shown a continuous increment of output power and gain with pump increment. The system does not exhibit the clamping phenomena due to the continuous increment of the upper level, N_2, by the pump power as it increases. The noise figure for the FBG-clamped system decreases slightly with pump power with the lowest noise figure of 5.4dB obtained at the maximum pump power. It is also exhibited that the noise figure for the FBG-clamped system is much lower than the open system. Higher feedback laser power is shown to give a broader unsaturated regime, but the gain maximum is smaller. The signal gain increases linearly with the feedback laser attenuation and then saturates at high attenuation regions. As attenuation increases, the power of the oscillating laser reduces and it contributes to a reduction in the mode competition, which causes the gain to increase until the saturated region is reached.

The fabricated FBG also is found to be applicable in fiber laser system. A fiber laser system with a different FBGs as an optical feedback component is studied and compared in this work and presented here. In this study, the laser performance is found to be dependent of FBG reflectivity. Higher reflectivity FBG is shown to give a higher peak power as well as slope efficiency. Increment of the grating reflectivity increases the intensity of the circulating light in the cavity. Higher output and slope efficiency are obtained due to higher stimulated photons in the oscillation increasing the stimulated emission rate. However, for the very high reflectivity and very broad bandwidth FBG such as FBG 4, there are 2 modes present in the cavity at high pump power, which is suspected to be due to gain competition in the medium [5]. Once the dominant mode saturates, the second mode starts to grow since the gain is wavelength dependent and the gain profile is not entirely homogeneous spatially and spectrally. The best performance is shown by a laser system with FBG 3, which has a 97.4% reflectivity with a 3dB bandwidth of 0.32nm centred at a wavelength of 1553.4nm. This laser has an extremely low threshold of 3.4mW, spectralwidth of 0.02nm limited by the resolution of the OSA, and slope efficiency of 12.5%. It is expected that improved slope efficiency would be found by increasing the EDF length, using an EDF of higher erbium concentration and reducing the cavity loss. Tuning of the FBG laser is demonstrated by putting the FBG section into an electric furnace. A continuous tuning range of 0.9nm is obtained by varying the fiber temperature from 39°C to 126°C. It is also expected that improved tuning range and tuning response would be found using a grating stretcher or strainer.

This work has shown that high reflectivity FBGs can be produced with an apparatus that is considerably less expensive than pulsed UV systems. The fabricated FBGs have been shown to be applicable in the gain clamped EDFA and fiber laser systems. This being a preliminary study on the FBG, there is still scope for more work. For example, this technique can be expanded to fabricate apodised, chirped and other types of FBG. Other characteristics such as index modulation in the grating also can be studied in future work. This FBG also could be extended to other types of applications such as wavelength selective devices [6], grating-based sensors [7] etc.

References

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