CHAPTER 7: CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

The focus of the work in this thesis is on three aspects – characterization of the physical, linear and non-linear optical properties of GO synthesized by a novel simplified Hummers' method, using the as prepared GO as a SA for laser *Q*-switching and light polarization. GO with a large lateral dimension is produced with a high degree of oxidation. It is found that the GO possess a modulation depth of ~10% and a low saturation intensity of ~7.3 $kWcm^{-2}$.

A GO-based *Q*-switched pulsed fibre laser is achieved. *Q*-switching of fibre laser using GO as a SA device is demonstrated. The GO-based device is well fitted for passive *Q*-switching of fibre lasers in the 1550 nm spectral range. The 'dip-coating' method has proved to be viable for fabricating the passive device for *Q*-switching of lasers. On the other hand, using GO in 'paper' form as a passive SA, *Q*-switching operation of a fibre laser can be realized as well. Both the material deposition method and 'paper' form of GO allow for cost-effective, massive scalability and easy realization of a SA medium.

For comparison purpose, a rGO based *Q*-switched EDFL is set up and the performance is compared with that of GO based *Q*-switched EDFL. Overall, no significance difference is observed. The nonlinear optical properties of GO is still well-preserved. In addition, its non-zero bandgap that allows tunability would enable its optoelectronic properties to be tailored to suit various applications.

Finally, using Bismuth-based erbium-doped fibre as a new laser gain medium, a compact *Q*-switched fibre laser is successfully demonstrated using 21 cm long Bi-EDF and a GO based SA. Besides being capable of generating *Q*-switched pulses, the laser is also tunable over the C-band.

A broadband waveguide polarizer with high extinction ratio has been demonstrated in a polymer waveguide coated with GO film deposited using the drop-casting method. The polarization effect of the GO waveguide polarizer has been shown to be a result of the anisotropic complex dielectric function of GO film. The extinction ratio of the GO polarizer is dependent on the GO film thickness. The average extinction ratio is 38 dB between 1530 nm and 1630 nm, with the highest extinction ratio of 40 dB measured at 1590 nm and the lowest value of 35.5 dB measured at 1530 nm. The extinction ratio is achieved with only ~1.3 mm of GO coating length along the propagation direction, and it is also the highest value ever reported upon the completion of this work to the best of knowledge.

GO differs from graphene due to the many chemical groups on the surface. GO itself is a non-stoichiometric compound of carbon and oxygen. Elemental analysis has revealed that the carbon-oxygen ratio of GO is close to 2:1. The uniqueness of this material is that the ratio can be controlled at any value between these limits and the material at a different value of carbon-oxygen ratio has different electrical and optical characteristics. Moreover, the chemical group on the surface of GO is chemically active and can easily be functionalized, which is a great advantage of the material and thought to be a potential material for vapour and liquid chemical sensors. Last but not least, the material is hydrophilic. Considering the fact that graphene is highly hydrophobic, GO disperses reasonably well in the water. Due to its high solubility, GO is promising for making new types of material, especially for making nano-composite, by just mixing with other material.

7.1 Future Work

Significant results have been achieved using GO as a passive SA for *Q*-switching. The non-linear optical properties have been exploited and many optical devices have been successfully fabricated and tested. The understandings of the physical structure and optical properties are rapidly increasing and becoming more established. For more practical applications, GO-based devices must operate reliably and be able to be customized according to the needs of the particular application.

- Thickness control

In the current synthesis method, thickness of the GO film is determined by the amount of chemical solutions used and it also depends strongly on the duration of oxidation. It is difficult to yield accurately controlled thickness for the final GO film produced. It is also a challenging issue to achieve desired film thickness. Thus new ways to prepare thickness-controllable GO robust films systematically are essential to extend the application of GO thin film into wider areas, such as *Q*-switching and mode-locking of diode lasers.

- Laser pulse energy scaling

The main objective of *Q*-switching is to obtain giant pulses with high pulse energy – useful in material processing, holography, metrology, 3D microfabrication and many others. Hence, pulses with high energies are essential. Pulse energy can be controlled by manipulating the pulse repetition rate. Low repetition rates enable high pulse energy. One proposed way to manipulate the repetition rate is to control the GO film thickness. Studies could be devoted to investigate the relationship between film's thickness and repetition rate, so as to bring into existence a novel method of increasing the pulse energy. The 'drop-casting' method proposed in this thesis could be further improved by examining the number of drops applied and its association with the thickness or number of layers of GO.

- Improved device structure

In this work, the GO films are coupled into a optical fibre system by ‘sandwiching’ them between two fibre ferrules. While it has the advantage of easy preparation, it unavoidably leads to non-saturable losses due to beam divergence inside the film. This will certainly degrade laser performance. It may be overcome by using anti-reflection coating and protective coating for the SA, for which theoretical and experimental in-depth studies on certain parameters (device loss, saturation fluence, recovery time etc.) are required.

- Anisotropic dielectric properties studies

GO is found to exhibit anisotropic dielectric properties. Studies could be devoted to the theoretical aspect of the dielectric anisotropy, which is expected to lead to differences in propagation loss for different polarization states. It can be used to provide the function of polarization selection in a optical waveguide.