Preface

At the time of writing this preface, the field of gravitational wave detection is very much focused on the installation of the second-generation upgrades to the first-generation detectors. Enhanced LIGO is far along in the process of becoming Advanced LIGO, and Virgo+ is being upgraded to Advanced Virgo. Both these upgrades are expected to bring a tenfold increase in broadband sensitivity, and as a result usher in the era of the first direct gravitational wave detections. Work has also begun digging the tunnels for the underground Japanese detector Kagra, which aims to reach a sensitivity similar to Advanced LIGO and Advanced Virgo, and GEO600 has been upgraded to GEO-HF with much improved high-frequency sensitivity. It is an exciting time in the field, with a great sense of anticipation for the challenges to come in commissioning the second-generation detectors to design sensitivity, and also of course for the first detection itself.

When I began my Ph.D. studies 5 years ago, the gravitational wave detection landscape was a little different, though no less exciting. The design and construction of the Advanced detectors still constituted a major part of the community's efforts, but it was also a time of particularly rich and varied research into new technologies that might be used to improve the sensitivity of detectors of the second generation and beyond. During the course of my Ph.D. studies, many new technologies were being investigated by the community at large for the gravitational wave detectors of the future. To take just one example, I saw squeezed light injection make the leap from table-top demonstrations to playing a key role in boosting the high-frequency sensitivity of GEO-HF, as well as being implemented on the Hanford LIGO interferometer. I was fortunate enough to spend my Ph.D. studies investigating another such technology, although one significantly younger even than squeezed light in the context of gravitational wave detectors: the use of higher order Laguerre-Gauss modes as a way of reducing thermal noise.

The sensitivity of the next generation of interferometric gravitational wave detectors will be limited in part by thermal noises of the optics. It was proposed in 2006 that using higher order Laguerre-Gauss (LG) beams in the interferometers can reduce this noise [1]. This thesis documents the progress made in assessing the compatibility of higher order LG beam technology with the existing precision interferometry framework used in the gravitational wave detector community.

Chapter 1 gives an introduction to the topic of gravitational wave detection. This includes a brief description of the theoretical basis for gravitational waves, a short history of gravitational wave detection experiments, a description of some of the leading interferometric gravitational wave detectors, and the principal noise sources that limit their sensitivity.

Chapter 2 provides an explanation of the technique of using higher order laser modes to reduce the levels of test mass thermal noise in gravitational wave detectors. This includes an overview of the relevant test mass thermal noise processes, a description of Laguerre-Gauss (LG) modes and Hermite-Gauss (HG) modes and the noise reduction factors for a range of LG and HG modes.

Chapter 3 describes the results of simulation investigations into the use of higher order LG modes in gravitational wave interferometers. Section 1 of this chapter describes simulation work led by Simon Chelkowski at the University of Birmingham, using the interferometer simulation software Finesse [2] to investigate the interferometric performance of LG modes in gravitational wave detectors. This study showed that the LG_{33} mode is compatible with the Pound-Drever-Hall (PDH) longitudinal control scheme [3] and the Ward technique for alignment control [4]. A sensitivity study was performed for the LG_{33} mode in an Advanced-Virgo-like detector, with the result that the LG_{33} mode could offer a potential increase in the observed gravitational wave event rate by over a factor of 2. Many of the results shown in this section are also presented in [5].

Although I was not directly involved in this work, much of the work described in Chap. 4 was aimed at experimentally verifying the results of these simulations. As a result I have reproduced several of the results, and become very familiar with the simulation code used. The code is included in Appendix B.1.

Section 2 of this chapter describes simulations investigating the means of LG mode generation by interaction with a phase modulating surface. I wrote several scripts and functions in Matlab to produce these results, some of which are included in Appendix B.2. The phase profiles that I designed during this work were used to produce higher order LG modes using a spatial light modulator, as described in Chap. 4, and later on as the basis for designing the etched diffractive optic used for the experiments described in Chap. 5.

Chapter 4 reports on the work that I led and carried out in table-top laboratory investigations of LG mode interferometry. This work included the generation of higher order LG modes using a spatial light modulator, and showed for the first time the feedback control of an optical cavity on resonance for higher order LG modes. An increase in the purity of LG_{33} modes from 51 % to over 99 % upon transmission through a mode cleaner cavity was shown, and the decomposition of a helical LG_{33} mode into two sinusoidal LG_{33} modes by interaction with a triangular optical cavity was also experimentally demonstrated. The main results of the work described in this chapter were published in [6].

Chapter 5 describes the work carried out towards a demonstration of LG_{33} mode technology at the Glasgow 10 m gravitational wave detector prototype. Section 1 explains the crucial issue of higher order LG mode degeneracy in optical cavities, which we aimed to investigate with the prototype experiments.

The results of simulation work into the mode degeneracy issue in which I was involved, but which was led by Charlotte Bond, are briefly reported in this section, and more fully in [7].

Section 2 of this chapter describes the design of the etched diffractive optic used for generation of LG_{33} modes for the prototype experiment. This diffractive optic was also used for the high-power LG mode experiments recently carried out at the AEI in Hanover, in which I was also involved and which are reported in [8].

These designs were made in collaboration between myself and the company Jenoptik.

Section 3 of this chapter describes the LG_{33} mode generation optical path that I designed and installed for the experiments at the 10 m prototype in Glasgow.

Section 4 reports on the methods and results of the investigation into the performance of the LG_{33} mode in a 10 m suspended optical cavity at the Glasgow prototype. This work was performed in collaboration between members of the interferometry groups in the University of Birmingham and Glasgow University. I was heavily involved from both sides, spending several weeks at the facility in Glasgow, as well as assisting in simulation efforts from Birmingham. The work described here is also reported in [9].

This work has provided useful insights into the compatibility of LG modes with larger scale interferometer systems, highlighting the issue of LG mode degeneracy within high finesse cavities. This remains the main difficulty to be overcome before the LG mode technology can be implemented in full scale detectors, although results presented recently in [10] suggest that there may already be a solution to this problem on the horizon.

Chapter 6 presents a summary of the work reported in this thesis and the conclusions that I have drawn from it. A brief discussion of the outlooks and prospects for LG mode technology in future gravitational wave detectors is also presented in this chapter.

Appendix A consists of reduction factors for higher order modes test-mass thermal noises other than coating Brownian noise. The bulk of the calculations are from references [11] and [12], but are presented here after scaling to account for the different clipping losses associated with each mode.

Appendix B consists of the FINESSE master input file written initially by Simon Chelkowski for producing many of the plots shown in Sect. 1 of Chap. 5, as well as the Matlab scripts and functions written by myself and others for producing the results shown in Sect. 2 of Chap. 5.

Gainesville, FL, USA, 30th May 2013 Paul Fulda

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