OPTICAL COATINGS AND THERMAL NOISE IN PRECISION MEASUREMENT

Thermal noise from optical coatings is a growing area of concern, and overcoming limits to the sensitivity of high-precision measurements by thermal noise is one of the greatest challenges faced by experimental physicists.

In this timely book, internationally renowned scientists and engineers examine our current theoretical and experimental understanding. Beginning with the theory of thermal noise in mirrors and substrates, subsequent chapters discuss the technology of depositing coatings and state-of-the-art dielectric coating techniques used in precision measurement. Applications and remedies for noise reduction are also covered.

Individual chapters are dedicated to specific fields where coating thermal noise is a particular concern, including the areas of quantum optics/optomechanics, gravitational wave detection, precision timing, high-precision laser stabilization via optical cavities, and cavity quantum electrodynamics. While providing full mathematical detail, the text avoids field-specific jargon, making it a valuable resource for readers with varied backgrounds in modern optics.

Gregory Harry has worked in the field of gravitational wave detection for over 15 years and is currently the Optics Chair and Coating Cognizant Scientist for the Laser Interferometer Gravitational Wave Observatory (LIGO), and Professor at American University, Washington DC. He is amongst the pioneers of coating thermal noise research.

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Foreword

As Lord Kelvin was renowned for saying – "to measure is to know" – and indeed precision measurement is one of the most challenging and fundamentally important areas of experimental physics.

Over the past century technology has advanced to a level where limitations to precision measurement systems due to thermal and quantum effects are becoming increasingly important. We see this in experiments to test aspects of relativity, the development of more precise clocks, the measurement of the Gravitational Constant, experiments to set limits on the polarisation of the vacuum, and the ground based instruments developed to search for gravitational radiation.

Many of these experimental areas use laser interferometry with resonant optical cavities as short term length or frequency references, and thermal fluctuations of cavity length present a real limitation to performance. This has received particular attention from the community working on the upgrades to the long baseline gravitational wave detectors, LIGO, Virgo and GEO 600, the signals from all likely sources being at a level where very high strain sensitivity – of the order of one part in 10^{23} over relevant timescales – is required to allow a full range of observations. Research towards achieving such levels of strain measurement has shown that the thermal fluctuations in the length of a well designed resonant cavity are currently dominated by those due to mechanical losses in the dielectric materials used to form the multi-layer mirror coating used, with the fluctuations of the mirror substrate materials also playing an important part.

Now that the importance of thermal noise in coatings and substrates is of clear importance in a range of precision experiments using optical cavities, it is very timely that a book be dedicated to these issues, and that the theoretical and experimental physicists at the forefront of their field from many laboratories around the world, have collaborated together in writing this.

The book is unique in that it ranges from discussions of the theoretical basis of thermal noise in mirrors and substrates, through the technology of depositing coatings and the techniques for measuring mechanical loss and thermal noise to the importance of this noise source in a range of applications. The real challenge of bringing this about will become very clear to the reader as will the rewards to be gained in areas such as precision timing and gravitational wave detection, these areas being well described by another quotation of Lord Kelvin – "When you are face to face with a difficulty, you are up against a discovery."

Professor James Hough, Kelvin Professor of Natural Philosophy,
University of Glasgow, January 2011

Preface

Dedicated to Robert Kirk Burrows

In 1999, I was a young postdoc moving to Syracuse University to work on LIGO, which had been a dream of mine since I was first introduced to gravitational wave detection as an undergraduate in Kip Thorne's class at Caltech. I had done my PhD in gravitational wave detection, but using the older technology of resonant masses rather than LIGO's laser inteferometry. I was concerned that my background would not prove appropriate. I soon found a common issue, thermal noise, that I was able to focus on. Beyond just a good fit for me, thermal noise was actually a topic in flux within LIGO at the time. A talented young theorist at Caltech named Yuri Levin had just shown that the optical coatings on the LIGO mirrors could well contribute much more thermal noise than anyone had anticipated. What was missing were realistic numbers to plug into Yuri's formulas to see just how big of an impact coating thermal noise might have. This became one of my principal roles in LIGO, as part of a group of experimentalists interested in this question at Stanford, Glasgow, as well as Syracuse and other collaborating institutions.

Since then, we in LIGO have found that coating thermal noise is a very important limit to sensitivity, and we have engaged in over a decade of theoretical, experimental, and modeling work to better understand and reduce it. One of the key difficulties was that we had to engage coating thermal noise within the strict limits of optical performance, as LIGO coatings also have to satisfy some of the strictest specifications on optical absorption, scatter, uniformity on a large scale, and other more conventional optics concerns. In the last few years, I started to see that other precision measurement fields were also hitting the same coating thermal noise limit.

Collaboration between fields on coating thermal noise started with a discussion in a bar in Harvard Square between myself and Markus Aspelmeyer, having been introduced by Professor Nergis Mavalvala whose research interests overlap with both of ours. I saw that a workshop on coating thermal noise involving researchers from many precision measurements fields as well as coating technologists, optical engineers, and others could be mutually beneficial. We held this workshop in March of 2008, and it is still accessible on the web at http://www.ligo.mit.edu/∼gharry/workshop/workshop.html.

Finally, this book came out of late night conversations with my graduate school roommate and friend, Kirk Burrows, during our annual vacations on North Carolina's Outer Banks. He would always encourage me to write a book, so after the workshop had proved a success and the opportunity with Cambridge University Press presented itself, I decided the time was right. All of us who have worked to make this book happen hope it proves valuable to both those currently in the trenches battling coating thermal noise and all the other coating issues discussed herein, but also to researchers in new fields just coming up to these limitations.

This book, like any book, is the result of many people's hard work, inspiration, dedication, and collaboration. The editors and authors would like to especially thank Matt Abernathy, Juri Agresti, Warren Anderson, Craig Benko, Eric Black, Birgit Brandstätter, Aidan Brooks, Gianpietro Cagnoli, Christof Comtet, Rand Danenberg, Carly Donahue, Raffaele Flaminio, Ray Frey and the entire LIGO Scientific Collaboration Publication and Presentation Committee, Daniel Friedrich, Peter Fritschel, Eric Gustafson, Ramin Lalezari, Yige Lin, Jean-Marie Mackowski, Andrew McClung, John Miller, Nazario Morgado, Mark Notcutt, Laurent Pinard, Takakazu Shintomi, David Shoemaker, Matthew Swallows, Toshikazu Suzuki, Takashi Uchiyama, Akira Villar, Stephen Webster, Valerie Williams, Dal Wilson, Hiro Yamamoto, and the post-graduate class in Advanced Electromagnetics at the University of Sannio for useful input and feedback on chapter drafts. Some material in this book is based upon work supported by the United States National Science Foundation under grants 0757058 and 0970147. Any opinions, findings, and conclusions expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We would also like to thank the Italian National Institute for Nuclear Physics (INFN) for financial support.