Preface

For many decades, research in quantum mechanics was largely concentrated on two areas: on methods for computing the energy levels and wavefunctions for states of individual particles in potentials, and on computing the statistical properties of many-particle quantum systems. Studying these two regimes has led to a progressively deeper understanding of the fundamental physics of many types of systems, ranging from single atoms to superconductors. It also led to some of the most important technological advances of the twentieth century, including the development of the laser and the transistor.

In recent decades, there has been a major shift of interest, in which the study of quantum few-particle systems (most commonly two or three particles) has become a primary focus. In particular, the study of *entangled* systems has played an increasingly large role, leading to a number of new, previously unknown effects, such as ghost imaging, quantum teleportation, entanglement swapping, and nonlocal interference. More or less simultaneously, the study of information in quantum systems has gained new prominence. Combined with the idea of entanglement, this has led to an explosion of interest in the topics of quantum computation and quantum communication, as well as new methods for making ultra-precise measurements.

In this book, we explore some of the new developments that have arisen from the idea of entanglement, sometimes in conjunction with quantum information theory, as applied to optical systems. In particular, emphasis is placed on how these developments in fundamental science have led to new or improved methods for carrying out practical applications. The goal is to introduce to nonspecialists a number of these applications. We assume that the reader has only a basic undergraduate-level background in quantum mechanics and classical optics, and so we spend the first few chapters covering the necessary background material on quantum optics, entanglement, and related subjects.

The list of possible topics that could be included here is so long that it would be impractical to try to give a comprehensive review. As a result, the choice of applications covered is determined partly by our own areas of expertise, as well as by the desire to give prominence to some areas which are less well known among nonspecialists. The most notable area that we chose to exclude is quantum computing, because it is a very widely known topic for which numerous excellent reviews already exist at both technical and popular levels. The applications that we cover fall generally in the areas of communication (including cryptography), imaging, and measurement.

The basic quantum-mechanical ingredients that are used repeatedly in these applications are superposition principle, entanglement, and the inability to unambiguously discriminate between non-orthogonal states. In general, these novel aspects of quantum mechanics enable the methods described here to produce advantages over classical methods in a number of different contexts. For example, quantum methods can lead to:

- Improved contrast in imaging.
- Improved resolution and sensitivity in measurements of quantities such as phase, dispersion, and frequency.
- Increased visibility in interference experiments.
- Improved security in cryptography and communication.

In each of these examples, the use of classical correlation can lead to improvements, but there is usually a limit beyond which a system can only go if it is entangled. For example, it can be shown that when interference fringes are measured in coincidence counting (intensity correlation) experiments, classical correlations between the particles arriving at the detectors can never lead to interference visibilities above $\frac{1}{\sqrt{2}} \approx 71\ \%$; however, entangled systems can have visibilities approaching 100 %.

The goal is to make the methods presented here accessible to both engineers and physicists from a diverse range of backgrounds, so Chap. 1 and the appendices include much of the required background material needed for a mathematically literate reader from other areas to follow the rest of the book. This includes a very brief overview of quantum mechanics in Chap. 1 and a review of optics in Appendix A. The remaining appendices include additional background material in more specialized topics such as turbulence and phase matching in down conversion; these topics are all used at various points in the main text. The review of quantum mechanics in Chap. 1 places emphasis on entanglement, which is central to many of the subsequent chapters. In Chap. 2, we give a survey of some relevant topics in quantum optics. Chapters 3–9 then give detailed discussions of a number of recent applications, ranging from high-precision aberration-canceled and dispersion-canceled measurements, to ghost imaging and quantum cryptography.

The essential material needed to follow the rest of the book is covered in the first two chapters. The remainder of the chapters can be read more or less independently of each other, according to the interests of the reader. Some of the chapters in this book form a greatly expanded treatment of material first presented as a series of talks in the *Advanced School on Quantum Foundations and Open Quantum Systems* held in João Pessoa, Brazil, July 16–28, 2012.

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