Quantum evolution

The optical world has long been the perfect playground for exploring quantum mechanics and its applications. Now, improvements in the fabrication of optoelectronics and integrated optics are promising dramatic enhancements to the capabilities of quantum communication and computing.

In classical mechanics, life is simple. Particles are particles, waves are waves, and we can know with certainty where something is and what state it is in. However, as any student who has studied physics will tell you, in the quantum realm the situation is far more complex. This issue of *Nature Photonics* has a special focus on quantum optics — the weird and wonderful world that results from combining quantum theory and light.

According to Gerard Milburn, an expert in quantum optics from the University of Queensland in Australia who has provided invaluable input for this editorial, the origins of the field date back to the 1960s. In particular, it began when Roy Glauber (then at Harvard University) initiated the study of the optical coherence of quantized electromagnetic fields — work for which he was later awarded a Nobel Prize.

"He showed that the quantum states of the field corresponded to well-understood coherence properties, as demonstrated in optical interferometry. Although this confirmed that certain field states would reproduce known results from classical optics, the new field of quantum optics indicated that uniquely quantum behaviour would become evident for certain types of scenario," Milburn explained. "Through the close interaction of theoreticians and experimentalists, the history of the subject between the 1960s and 1990s can be seen as a steady realization of this promise."

According to Milburn, the 1970s was the decade for studying the quantum features of photon-counting statistics, which culminated in the prediction and observation of photon antibunching. This was followed in the 1980s by a return to studying the complementary 'wave' aspect of light, with attention focusing on phase-dependent properties such as squeezing. In the 1990s, the non-classical aspects of entanglement became the major area of investigation, following the pioneering work on Bell's inequalities by Alain Aspect and others in the preceding decades.

The 1990s also saw a divergence in the community as the new fields of atomic condensates and quantum information made significant progress. Quantum optics became the perfect testing ground for the new ideas being developed in quantum information theory in the early 1990s, and it has achieved enormous success since then. Many of the more surprising predictions of quantum theory (such as teleportation and the violation of Bell's inequality) have been verified with astonishing reliability in quantum optics. Milburn explained the reason for this great success:

AUSTRALIAN NATIONAL UNIVERSITY

"At optical frequencies the laboratory is an extremely cold place. Thermal excitations at optical frequencies are usually negligible, and one can therefore probe quantum coherence without the obscuring effects of thermal noise. Of course, one must still contend with spontaneous emission and photon absorption," Milburn said. "Much of the progress in the field has come from mitigating these effects to achieve an extraordinary level of coherent quantum control, especially in the area of quantum communication protocols such as quantum key distribution."

So what does the future hold for the field? Quantum optical communication and computing will undoubtedly continue to produce significant achievements over the next decade. A Commentary by Tim Ralph and Ping Lam on page 671 of this issue highlights the recent progress in the implementation of quantum information protocols. Applications are currently limited by their hardware performance, particularly for photon detectors and reliable sources of on-demand single photons. The good news is that there is steady progress, as indicated by the Review on state-of-the-art single-photon detectors by Robert Hadfield on page 696, and by the Product Focus on commercial photon-counting equipment on page 738.

One very important recent development in the scaling of quantum optical systems for tackling more demanding tasks is the use of integrated optical circuitry, which opens the door to the tantalizing prospect of on-chip quantum optical experiments[1]. The Review by Jeremy O'Brien, Akira Furusawa and Jelena Vučković on page 687 details the exciting level of integration achieved, with these developments helping to avoid cumbersome set-ups (see image). Indeed, the use of such circuitry for performing Shor's algorithm — a method for finding the factors of prime numbers — was recently reported[2]. If future sources and detectors are integrated on-chip, more sophisticated quantum devices will undoubtedly result.

The applications of quantum optics are not only limited to communications and information processing. As Konrad Banaszek, Rafał Demkowicz-Dobrzański and Ian Walmsley explain in a Commentary on page 673, quantum theory also has an important role in defining the ultimate precision of metrology and measurement schemes. Indeed, by carefully preparing and exploiting quantum states it is possible to squeeze the uncertainty of measurements to a level beyond that usually achievable.

According to Milburn, quantum computing is the ultimate test of our ability to control the world at the quantum level, and it has already provided significant advances, especially in the form of measurement-based quantum computation. One of the key components, not only for quantum computing but for many quantum processes where time constants do not overlap well, is quantum optical memory. The recently proposed schemes for optical quantum memories are detailed in a Review by Alexander Lvovsky, Barry Sanders and Wolfgang Tittel on page 706.

Quantum optics will continue to play a part in the emergence of new technologies, but Anton Zeilinger (interviewed on page 677) explains that if we can learn anything from history, it is that the applications people will eventually benefit from are not the ones we are talking about today. ❒

References

1. Matthews, J. C. F., Politi, A., Stefanov, A. & O'Brien, J. L. *Nature Photon.* **3,** 346–350 (2009).
2. Politi, A., Matthews, J. C. F. & O'Brien, J. L. *Science* **325,** 1221 (2009).