Quantum Information Science in the Optics Curriculum

Bahaa Saleh
CREOL, The College of Optics and Photonics, University of Central Florida, Orlando, FL, USA
besaleh@creol.ucf.edu

Abstract: Optics is an essential backbone of quantum information science (QIS). Infusing QIS in the optics curriculum is much needed, but challenging. We report an approach transitioning from classical matrix optics to qubits and quantum gates.

Quantum information science (QIS) is an emerging area where fundamental principles of quantum physics are harnessed to achieve remarkable and far-reaching advances in information science and technology, promising exponential speed-ups in computing, demonstrating unparalleled security in communications and networking, and breaking long-standing classical limits of precision measurement. Progress in these areas continues to be challenging and is fueled by meaningful collaboration among scientists and engineers in diverse disciplines.

Optics is an essential backbone for QIS. The currently developed quantum hardware includes superconductors, trapped ions, cold atoms, quantum dots, NMR, optical lattices, and *photons.* However, no matter what hardware is used, photons provide transport of the quantum bits, communication, interconnections and networking, and enables applications mediated by light such as remote sensing, imaging, and metrology. It is therefore vital to prepare science and engineering students for the ongoing rapid advances in quantum science and emerging quantum technology.

The question is how to infuse basic quantum principles in the already dense science and engineering curricula. I believe that the best approach to teaching a new topic is to relate it to material the student already knows and routinely uses. In this case, the best stepping stone to the quantum bit (qubit) is matrix algebra (Jones calculus) of polarization modes.

Matrix methods are well-established essential tools that have enriched optics by facilitating the description of operations on two complex variables, such as two optical field components. The early work of R. Clark Jones in the 1950s introduced ground- breaking ideas in using matrix algebra to describe polarization, creating what has become known as Jones calculus. The textbook by A. Gerrard and J. M. Burch [1] is devoted to matrix applications in paraxial imaging and polarization, and the textbook by J. W. Blaker [2] covers geometric optics from a matrix perspective. In his textbook, A. Siegman [3] introduced matrix methods as a powerful tool for the design of optical resonators. Many other optics applications have also benefitted from the power of matrix algebra, including coupled waveguides, transmission and reflection in multilayered and stratified media, and propagation in periodic media, such as photonic crystals [4].

We believe that matrix optics is an ideal prelude to the quantum bit (qubit). The quantum state is simply the analog of the polarization state, the Bloch sphere is the same as the Poincare sphere, and quantum gates applied on the qubit are mathematically identical to familiar polarization devices. The student familiarity with coherence and partial polarization serves as a direct route to the quantum principle of mixed states, where the density matrix plays the role of the normalized coherency matrix. It is necessary however, to supplement this classical-quantum parallelism with the axiom of measurement in the quantum theory.

Linear systems theory and matrix algebra are sub-topics of the mathematical theory of linear vector space. The concepts of signals as vectors in a vector space, linear systems as mappings or operators in that space, and modes as eigenvectors, etc., are powerful tools that are widely used in electrical engineering and digital image science. But the theory of linear vector space is the principal mathematical foundation underlying quantum mechanics. The quantum state is described by a vector in a linear vector space, dynamical variables are operators, and the outcome of measurement of an observable is one of the eigenvalues associated with the

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modes. These are essential concepts in the physics curriculum, and are used in teaching semiconductor devices such as quantum wells. We can build on this knowledge to introduce QIS.

We have encouraged the adoption of the theory of linear vector space as the mathematical foundation of classical optics. Teaching optics from a perspective of linear vector space will enable optics students to rapidly learn quantum optics and quantum information science. It is hoped that this approach will facilitate the adoption of linear vector space principles as a basis for teaching optics, both classical and quantum.

The far-reaching similarities between classical and quantum systems is attributed to the underlying linear vector space foundation. The notion of separability in vector spaces comprising two bimodal vectors, which underlies quantum entanglement of bipartite systems, is common to both classical and quantum composite systems. These similarities are helpful in introducing two-qubit quantum gates. Quantum systems are of course differentiated by unique properties such as the inherent uncertainty of the outcome of measurement and fundamental issues such as violation of local realism and incompleteness of quantum theory.

Many of the concepts introduced in the bimodal space by analogy to polarization modes must be generalized to the infinite-dimensional function space (Hilbert space) in order to introduce the *photon*. This can be accomplished by highlighting the difference between the classical and quantum harmonic oscillator. Optics of the single photon is identical to coherent optics of two photons is very similar to optics of partially coherent light, where propagation is based on correlation of light at pairs of points. The only difference is in the interpretation of the results of measurement.

I have successfully used this approach to teaching quantum concepts in an optics course offered at CREOL. A textbook is in preparation [5].

3. References

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