Photonic information processing needs quantum design rules

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The quantum nature of light requires engineers to have a special set of design rules for fabricating photonic information processors that operate correctly.

In the century since Einstein postulated light's quantum nature—an event celebrated last year, along with SPIE's 50th birthday—the quantum revolution has progressed from formalizing the mathematical theory of the electron and photon, to a second wave that uses quantum phenomena for new information-processing technologies. These applications are found in fields as diverse as communications, cryptography, computing, and even imaging.

Since photons are the de facto information-encoding entity, this means photonic information processing often amounts to quantum information processing, which can be carried out on chips fabricated with very large scale integration (VLSI) techniques, such as the array of single-photon detectors shown in Figure 1, for significant cost reduction. Our experience with VLSI has taught us the importance of having good rules¹ that abstract away the underlying physics and allow engineers to design chips. This inspired us to consider an analogous set of quantum design rules (QDRs) for VLSI photonics.^{2,3}

Understanding the quantum rules

To establish correct engineering guidelines, we first need to understand the quantum rules that photons obey. We adopt the quantum path integral (QPI) formalism⁴ to avoid traps that arise from treating the photon as either a classical particle or a classical wave. Under this formalism, a photon propagating in free space is represented by an infinite set of QPI amplitudes ϕ_i between source s and detector d .

The probability for detecting a physical photon is determined by summing over all of these paths, and then taking the squared modulus of the result. Some eight quantum rules^{2,3} of this type will correctly calculate probabilities in VLSI information-processing devices. For example, in Figure 2, which shows a scat-

Figure 1. This device includes a 32×32 array of CMOS single-photon detectors.

Figure 2. Shown is one of infinitely many paths ϕ a photon can take going from source s to detector d . Path ϕ_1 includes an interaction with matter, an event denoted by $\mathcal{E}$, and two legs, ϕ_{1a} and ϕ_{1b} .

tering event $\mathcal{E}$, path ϕ_1 would be computed as the product of the two legs, ϕ_{1a} and ϕ_{1b} , an example of the 'AND-ing' rule. We have shown elsewhere that flawed claims can result when these rules are ignored.²

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Figure 3. The entangled biphoton may be viewed as a quantum path integral amplitude with idler and signal segments, i and s , created by event $\mathcal{E}$. D_1 , D_2 : Detectors. CC: Coincidence counter.

Entanglement, loops, and ghosts

We have extended QPI formalism to *entanglement*.^{2,3} The most common method for producing entangled ‘biphotons’ pumps a nonlinear crystal, such as beta-barium borate (BBO), with UV photons to create photon pairs whose total momenta and energy equal that of each pump photon. An entangled pair acts like the two-segment QPI amplitude shown in Figure 2. Figure 3 depicts the BBO crystal as the scattering event $\mathcal{E}$ in Figure 2, and detectors D_1 and D_2 as the source and detector, respectively. One biphoton (*signal*) propagates from $\mathcal{E}$ to detector D_2 in the expected way, but the *idler* photon propagates backward from D_1 to $\mathcal{E}$. The coincidence counter (CC) forms a closed circuit of paths.

Figure 3, as adapted in Figure 4, also explains how quantum ghost imaging^{5,6} works. Detector D_1 acts like a source for the idler photon passing through a focusing lens to the BBO crystal, which propagates the signal photon to the detector array D_2 . The ghost image appears only in the coincidence counts, focused in accordance with the thin lens equation.

Toward QDRs

With the photon rules in hand, we can discern some engineering-level QDRs. (i) Photons don’t interact with photons, but only the material comprising the device. (ii) The minutest change to the material comprising a quantum information device can completely alter its operation. (iii) The distinction between amplitudes and intensities made in Fourier optics becomes redundant: only quantum amplitudes lead to probabilities. (iv) The thin lens equation $d_i^{-1} + d_o^{-1} = f^{-1}$ still holds for quantum-ghost imaging devices.⁵ More experiments are needed to enumerate other QDRs, and that is a major thrust of our current research conducted in the Quantum Architecture Group at the Swiss Federal Institute of Technology Lausanne (EPFL; Figure 5).

Figure 4. This quantum ghost imaging device is topologically equivalent to the closed-circuit arrangement of Figure 3 with an interposing thin lens. d_o , d_i : Object and image distances.

Figure 5. The Quantum Architecture Group at the Swiss Federal Institute of Technology Lausanne uses this laser system to create entangled biphotons.

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