

Simple Photonics

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Abstract: Photonics is at once complex and fundamentally simple. We develop a quantum-optical field theory of multiphoton phenomena which brings to the linear, non-interacting field the concepts and phenomenology of condensed matter, while remaining exactly solvable.

Keywords: quantum optics; photon correlations; multiphoton states; non-classicality.

Photonics is a complex problem [1]. Even the one-photon case is far from being well-understood. For instance, common lore overlooks the basic meaning of single-photon emission, since, if it is good enough [2], it becomes a type of temporal liquid-light with the same correlations in time as those of a liquid in space [3]. The bulk of one-photon physics is thus currently focused on engineering gaseous light, whereas for quantum applications, one should be in pursuit of viscous, liquid, or even quasi-crystalline (temporal) light instead [4]. When it comes to two photons, the stage is predominantly occupied by SPDC sources, and much of the underlying two-photon physics has remained confined to particular cases of this community, sometimes with obfuscation from technicalities more proper to their art than to two-photon phenomena [5]. It has long been appreciated, however, that two-photon physics is not the same as the physics of two photons [6]. This can be best seen in the HOM effect, which also remains surprisingly little prospected, given how fundamental and important this case is. Obvious generalizations, e.g., to other quantum states, or to other spaces, have also remained largely confined to particular cases (SPDC, two points only, etc.). Ultimately, one has to address the problem of multiphotons distributed in multiple modes, and study their dynamics as well as processing.

Photonics is also fundamentally simple, all things considered, thanks to its intrinsic linearity. The absence of interactions does not make it trivial, because it still features interferences and this is rich enough to make it complex in the sense of universal and technologically relevant [1]. But it gets rid of a lot of technical and mathematical difficulties, of the need for sophisticated approximations, heavy numerical methods, etc. A simple quantum-optical field theory can be established [7] that brings all the degrees of freedom of condensed matter physics (strongly-correlated fields in spacetime) without the rich and interesting but, in fact, secondary phenomenology that is also present in classical physics (nonlinear physics). In this way, one can tackle the multiphoton spacetime dynamics in essentially exact terms. As a starting point, the spatial correlations between N photons upon collapse of their wavefunction already brings to the fore central concepts of condensed-matter physics: symmetry breaking, correlations, phase transitions, quenching, self-averaging, universality classes, quantum and quantum-optical coherence (two different concepts), etc., and new insights such as a variant of the ergodic hypothesis, contrasting ensemble vs. quantum averages [8]. One and two-photon physics emerge as mere particular cases of a broader conceptual picture, in which they get unified and their understanding considerably simplified. Another fascinating problem at the heart of any applied prospects of photonics, concerns the non-classicality of the states and the nature of the resources it can provide for computation [9]. A de Finetti representation of the quantum state can establish when a state features genuine correlations or whether those occur in the disguise of more mundane and classical statistical factors [10]. No less interesting, foundational aspects of the problem find in photonics their most fruitful platform. Quantum Bayesianism and the most fascinating concepts which derive from this interpretation, such as local friendliness [11], promise spectacular developments with modern photonics, especially when interfaced with AI providing simple yet realistic agents to serve as observers in their Wigner bubbles. A typical open question illustrative of the potential of multiphotonics is whether a Simpson paradox in a multiverse—such as the one accessed by the generalized P function—could explain quantum correlations of non-Gaussian states just like the Glauber-Sudarshan P function explains boson correlations of classical states [12].

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