Interferometry Using a Multi-Photon Tunneling Coupler

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Interferometers involving special quantum states can show fascinating and counter-intuitive effects. Recent discussion of photon DeBroglie waves has provided a particularly interesting perspective [1, 2]: the basic idea is that whenever photons display *correlated* dynamics as they pass through a nonlinear interferometer, a description in terms of multi-photon bound particles can be useful. Multi-photon particles behave quite differently from uncorrelated photons: a bound collection of N photons has total momentum $N\hbar k$. Interference of such particles has fringe period λ/N. This runs against our intuition for linear optics.

The Kerr coupler was proposed as a potential implementation of the above interferometer. The Kerr effect can provide a “binding force,” holding a packet of photons together as it passes through the coupler. A number of issues must be addressed in any realistic design—including loss and temporal pulse shape. Here we study the basic effect using a simplified two-mode model. In this model, $\hat{a}_1$ and $\hat{a}_2$ correspond to local transverse modes of two waveguides, and are propagated using the Hamiltonian,

$$\hat{H}_{\text{field}}(t) \quad = \quad -\mu(t)(\hat{a}_1^\dagger \hat{a}_2 + \hat{a}_2^\dagger \hat{a}_1) - \kappa(\hat{a}_1^\dagger \hat{a}_1^\dagger \hat{a}_1 \hat{a}_1 + \hat{a}_2^\dagger \hat{a}_2^\dagger \hat{a}_2 \hat{a}_2). \tag{1}$$

This Hamiltonian includes the Kerr effect in each waveguide ($\sim \kappa$) and linear coupling between them ($\sim \mu(t)$). The Kerr term introduces a field energy proportional to $(\hat{n}_1 - \hat{n}_2)^2$—an energy of localization of the field—which partially counteracts classical coupling.

Equivalent models have been extensively studied in the context of various physical systems [3, 4, 5]. In fact, our multi-photon coupling concept corresponds exactly to the tunneling of spins in some molecules. The usual tunneling properties are fundamental to a multi-photon switching effect. A multi-photon packet can tunnel from one waveguide to another without the photons coupling across independently.

We have explored theoretically the DeBroglie-wave interferometer shown in Figure 1. It consists of two nonlinear couplers and a conventional phase shifter in a Mach-Zehnder configuration. We have demonstrated the basic physics by direct numerical solution of Schrödinger’s equation, with no special approximations, as shown in Figure 2.

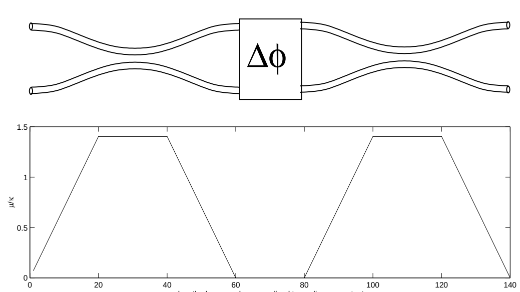

Figure 1: Conceptual sketch of nonlinear coupler with adiabatic variation of linear coupling.

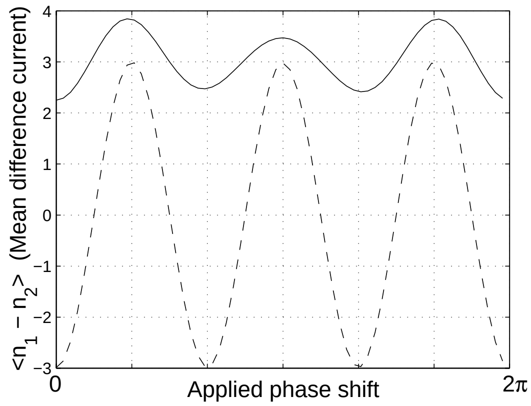

Figure 2: Numerical results: fringes with enhanced phase sensitivity are calculated for a photon-number state and a coherent state. The number uncertainty of the coherent state reduces the contrast of the fringes, but leaves the basic physics of photon tunneling intact.

References

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