Quantum Interference in Monolithic Nanophotonics

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ABSTRACT

In this talk, monolithic photonics architectures that enable deterministic splitting of entangled states of light will be discussed. In addition, quantum state engineering using the same architectures will be presented exhibiting characteristics that are unique to integrated architectures.

Keywords: Quantum Photonics, Quantum States of Light, Quantum State Engineering, Quantum Interference.

1. INTRODUCTION

All-integrated quantum photonics is far more than the miniaturization of the bulk-optics paradigm. Quantum state engineering in these structures presents both new challenges and unique opportunities. Their highly dispersive nature means that on-chip devices can exhibit state dependent behaviours that differ from those of their bulk-optics counterparts. Here we focus on the manipulation of entangled twin photons and their properties.

Photon pairs are generally created together within the same guided mode via optical nonlinear processes [1]. Separating these photons into different waveguides for independent manipulation is not always a trivial task, especially if the photons are highly tunable. Conventional means of separating them are either non-deterministic (50:50 mode splitting) or place restrictions on their properties (e.g. wavelength or polarization splitting). A more elegant solution is to utilize quantum interference, which in principle enables deterministic separation of any arbitrary two-photon state [2]. We will discuss this solution and how its performance can depend on the dispersive properties of the interference-mediating integrated device [3].

The very same dispersive effects can be exploited for novel implementations of state engineering, including in-situ tunability over spectral entanglement and tunable photon time-ordering. We will discuss how this grants dispersive mode-couplers an expanded suite of capabilities that their bulk-optics counterparts lack [4].

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2. DETERMINISTIC PAIR SEPARATION THROUGH QUANTUM INTERFERENCE

In the famous Hong-Ou-Mandel (HOM) effect [5], two indistinguishable photons arriving at opposite inputs of a 50:50 2x2 mode coupler coalesce into a bunched output state through quantum interference. The time-reversed process can be used to deterministically separate twin photons generated on-chip [2]. So long as the joint photon state $|\psi\rangle_i$ is the same for both inputs A and B, the properties of each individual photon (e.g. polarization, wavelength) can differ without impacting the probability of successful separation, in principle.

For on-chip quantum interference, it is implicitly assumed that the 2x2 mode coupler maintains a 50:50 splitting ratio over the twin-photons' entire joint spectrum. However, this is not necessarily the case for integrated devices such as a 2x2 directional coupler. The coupling strength $\kappa(\lambda)$ can be strongly wavelength-dependent, with the corresponding splitting ratio for a device of length L given by $\eta(\lambda) = \cos^2(\kappa(\lambda)L)$. For some combinations of twin-photon wavelengths λ_1 and λ_2, the coupler behaves as an ideal 50:50 beamsplitter (BS) having $\Delta\eta = |\eta(\lambda_2) - \eta(\lambda_1)| = 0$, while for others it behaves as an ideal wavelength de-multiplexer (WD) having $\Delta\eta = 1$.

The consequence is that on-chip quantum interference and the resultant separation probability can depend on the photon bandwidths and spectral entanglement, even if these photons have marginal spectra that perfectly overlap and are centered on a wavelength with $\eta(\lambda_0) = 0.5$. For a non-zero linear coupler dispersion given by $M = d\kappa(\lambda)L/d\lambda$, an increase in photon bandwidth $\Delta\lambda$ degrades the effect of quantum interference and gradually drives the separation probability towards its classical value of 50%, as per Figure 1. On the other hand, spectral entanglement has the effect of preserving quantum interference at large bandwidths, leading to a separation probability that increases with increasing Schmidt Number (SN). These dependencies, which are unique to dispersive integrated architectures, could be utilized to make on-chip test sites that can read out the spectral entanglement of an ensemble of states without requiring full quantum state tomography.

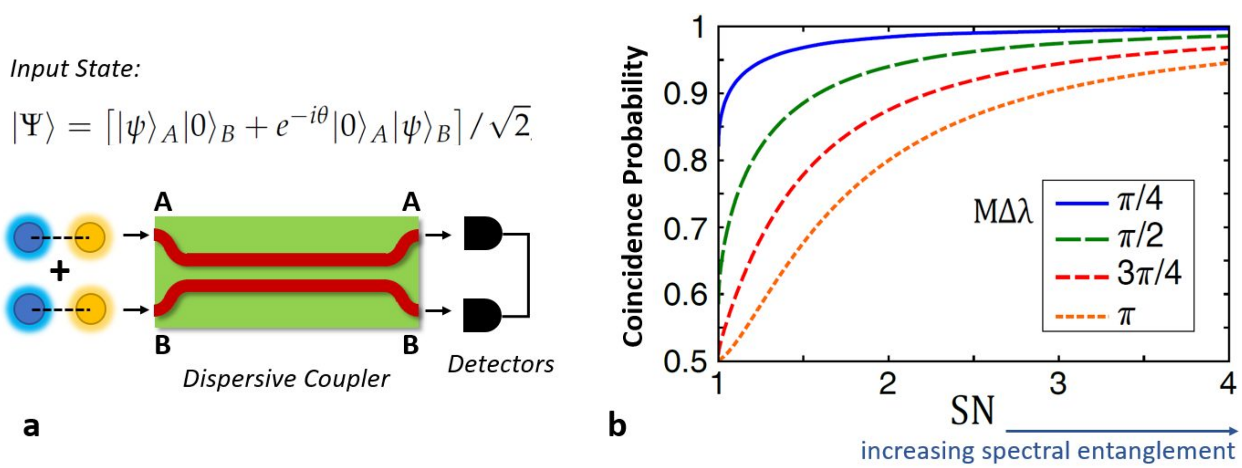

Figure 1: Influence of coupler dispersion and state properties on time-reversed HOM interference; (a) input conditions; (b) probability of obtaining a coincidence count (separated outcome) at the coupler output [4].

3. DISPERSION-ENABLED STATE ENGINEERING

Beyond its implications for two-photon interference, dispersion can allow integrated 2x2 couplers to play a far more versatile role in quantum circuits than their bulk-optics counterparts. A linearly-dispersive directional coupler can be tuned between the extremes of beamsplitter and WD behaviour by shifting $\kappa(\lambda)$ through electro-optic or thermal tuning. This offers in-situ control over the photon correlation properties. As illustrated in Figure 2(a), suppose a non-degenerate photon pair is injected into only one import port, and the output is post-selected for outcomes where these emerge separated. Let the input state be $|\psi\rangle_{in} = |\lambda_{01}\rangle_A|\lambda_{02}\rangle_A$ where λ_{01} and λ_{02} are the photon central wavelengths. A beamsplitter-like coupler response $\Delta\eta = 0$ reveals no information about the spectra at the output, giving the superposition $|\psi\rangle_{out} = [|\lambda_{01}\rangle_A|\lambda_{02}\rangle_B + |\lambda_{01}\rangle_B|\lambda_{02}\rangle_A]/\sqrt{2}$ which preserves the full spectral entanglement of the input state. However, a WD-like coupler response with $\Delta\eta = 1$ predetermines the wavelengths that emerge at each output port, giving $|\psi\rangle_{out} = |\lambda_{01}\rangle_A|\lambda_{02}\rangle_B$, which in turn alters the spectral entanglement of the post-selected output state. Figure 2(b) exemplifies how tuning $\Delta\eta$ between these two extremes provides selection over the output spectral entanglement. This technique could provide useful all-integrated capabilities for applications in light-induced matter correlations [6].

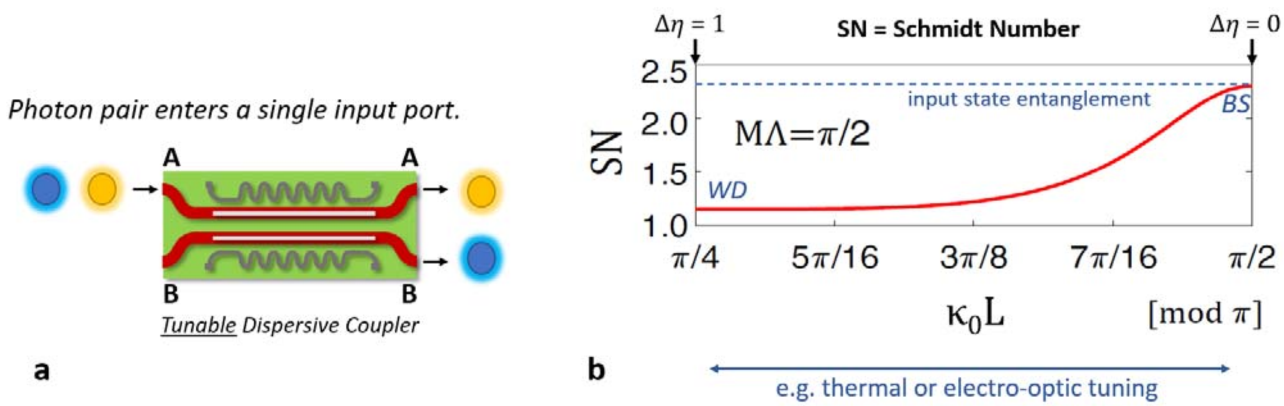

Figure 2: Dispersion-enabled control over spectral entanglement; (a) implementation; (b) dependence of output entanglement on coupler response, where $\Lambda = |\lambda_{02} - \lambda_{01}|$ is the photon pair non-degeneracy and κ_0 is the coupling strength at an arbitrary reference wavelength [4].

Using this same technique but adding a temporal delay to one of the output paths as in Figure 3(a) enables control over the photon time-ordering. This has applications in two-photon spectroscopy, where it can be utilized to toggle certain two-photon transitions on and off [7]. The general state at the coupler output is a superposition giving two possible outcomes: either λ_{01} is delayed relative to λ_{02}; or λ_{02} is delayed relative to λ_{01}. Each possibility corresponds to a different absorption pathway, and in certain materials these pathways interfere to suppress the two-photon absorption probability. When $\Delta\eta = 1$, the light is time-ordered, meaning that one photon wavelength always arrives before the other

(Fig 3(b)), and the transition is allowed. When $\Delta\eta = 0$, the light is not time-ordered, meaning that either wavelength can be absorbed first (Fig 3(c)), and the transition is suppressed. Hence, a dispersive coupler can provide useful capabilities enabling greater selectivity in spectroscopic and imaging techniques [7,8] in a practical all-integrated format.

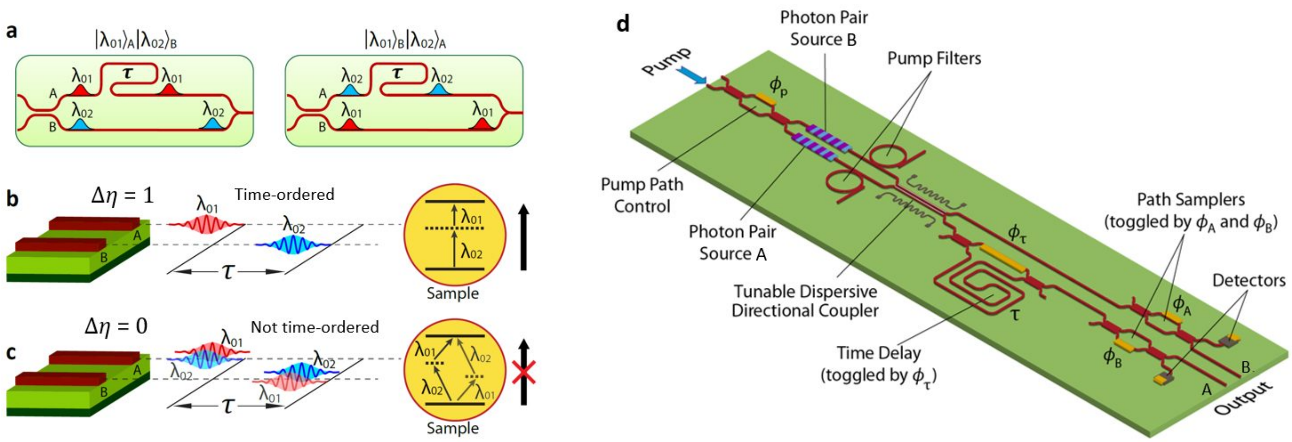

Figure 3: (a-c) Dispersion-enabled control over photon time ordering; (d) example of a monolithic photonic quantum circuit where a single dispersive coupler provides multiple functionalities (see text) [4].

The new dispersion-enabled capabilities described above enables a single dispersive coupler to play an extremely multipurpose role with a relatively compact footprint. In the quantum circuit depicted by Figure 3(d), the same coupler that provides interference-facilitated pair separation can also provide tunable spectral entanglement and tunable time-ordering, as well as on-chip state characterization capabilities due to the dependence of interference on bandwidth and entanglement.

4. CONCLUSION

Our work has shown that coupling dispersion in integrated device architectures influences quantum interference in novel ways, leading to new dependencies on bandwidth and spectral entanglement when this dispersion is sufficiently high. This same dispersion can be harnessed to provide new techniques for state engineering, allowing new methods of in-situ photon entanglement and correlation tuning from a single integrated device. We have therefore shown that conventional integrated devices can possess as-of-yet untapped capabilities that could be unlocked by fully harnessing their dispersive properties. Our analysis can be expanded beyond 2x2 directional couplers to other integrated devices with more exotic transfer functions, including interferometers and coupled waveguide arrays.

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