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Topological Quantum Photonics

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***Abstract*:** We review our experiments on the generation and propagation of quantum states of light in topological nanophotonic platforms, specifically, topological protection of biphoton states and path entanglement, and entanglement of different topologies.

1. Introduction

The field of topological photonics has developed quickly in the 15 years since its inception [1]. Stemming from earlier discoveries in condensed matter physics, this field combines concepts of photonics, geometry and mathematical topology: by engineering the geometry of photonic arrangements, the bands in the photonic dispersion relations can be engineered to possess non-trivial topologies, i.e. global properties that cannot be discerned locally and that cannot be changed by small continuous deformations.

Arguably the most important property of topological structures is the presence of topological edge-modes that arise at the interface of two materials with distinct topological properties. Light traveling in these modes can show enhanced robustness to certain types of defects and imperfections.

In the last few years, the field has evolved from purely fundamental discoveries toward real applications in quantum information, laser arrays, and sensing among others [2]. In this paper we review our work on the interaction of topology and quantum states of light [3].

2. Results

While the interaction of topology with quantum states of light has been extensively studied, only in the last few years we have seen an increased interest on understanding the interaction of topology with quantum states of light. While the origin of the protection for quantum light is the same as for electromagnetic light, i.e. the existence of topological eigenmode with increased robustness, the properties and the variables that become relevant when studying the interaction of topology with quantum light are not present in classical states, namely superposition and entanglement. Next, we discuss different ways in which topology can interact with quantum correlations: in the generation and propagation of quantum correlated photon pairs, in the protection of path entangled states, and in the creation of multimode entanglement across modes of different topologies.

2.1 Topological Protection of Biphoton Correlation

Multiphoton states are a key element in quantum information. Biphoton states – involving two photons with quantum correlations between them – are the simplest of those family of states.

In order to study topological protection of biphoton states we resort to the simplest topological model, the dimer chain [4], which relies on a bipartite lattice of coupled sites. In particular, we use a nanophotonic implementation of the dimer chain based on silicon waveguides (w=450 nm, h = 220nm, L=386um) with alternate short and long gaps between (gs = 173 nm; gl = 307 nm) [5]. In the middle of the lattice, we purposedly induce a defect by having two consecutive long gaps and this creates an interface between two mirror images of the dimer chain with different topological invariants that supports an edge mode, as shown in Fig.1(a).

Biphoton states can be created in this nanophotonic lattice by resorting to the inherently high nonlinearity available in the silicon waveguides. Specifically, we leverage degenerate spontaneous four wave mixing (FWM), a nonlinear Kerr effect in which two photons at the pump frequency disappear to create signal idler photons that are energy-time entangled [6]. By using a picosecond laser pump input in the centre of the long-long defect, we couple the pump to the topological edge mode. In turn, this pump gives rise to energy-time entangled photon pairs that are generated and propagate in the topological edge mode. At the output of the lattice we measured the biphoton correlation map by detecting and counting quantum correlation events between waveguides, as depicted in Fig. 1(b).

Next, we deliberately introduce random disorder in the position of the waveguides, which in turn creates disorder in the coupling strengths. We observe in Figs. 1(c) and (d) that certain features of the biphoton correlations remain unchanged under the presence of this type of disorder [6].

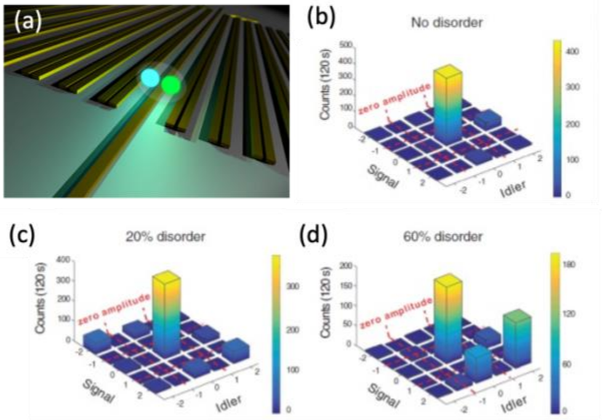

Fig. 1. (a) Silicon photonic dimer chain with long-long defect; (b-d) Biphoton correlation at the output of the lattice for 0%, 20% and 60% disorder in the coupling.

2.2 Topological Protection of Path Entanglement

Expanding on the results described in the previous section, we launched into demonstrating topological protection of path-entanglement [7]. To do so, we fabricated a lattice similar to the one described above but, in this case, with two-long long defects sufficiently far from each other so that there is no coupling between the two supported edge modes, see Fig. 2(a). We take a picosecond laser and split it in two branches, with each of them going to the centre of a different long-long defect. By taking advantage of the FWM-generated biphotons, we can now create path entanglement across the two topological modes, in analogy with Ref. [8].

The measured biphoton correlation at the output of this lattice shows strong signatures of topologically protected path entanglement, such as the localization in one of the sublattices (see dashed lines in Fig. 2(b)).

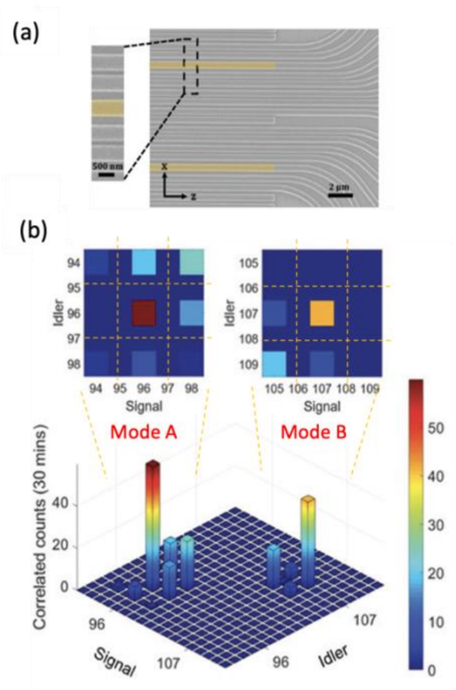

Fig. 2. (a) Silicon photonics lattice with two topological modes; (b) Correlation under 40% disorder in the coupling.

2.3 Entanglement between spatial modes of different topologies

So far, we have studied two cases in which the pump overlaps strongly with one topological edge modes and thence the FWM-generated biphotons have no choice but being created in the same mode. A more complex situation arises when several localized modes co-exist and compete for the biphoton population [9]. This situation can be created in a dimer chain with a short-short defect (Fig. 3(a)) that supports three localized modes: one of topological nature and two of trivial nature. When pumping in the center of such defect the FWM-generated biphotons can couple, in principle, to any of the nine possible biphoton eigenmodes: signal in the topological mode and idler in the trivial mode1, signal in trivial mode 1 and idler in the topological mode, and so on so forth. The resulting quantum state at the output of the lattice is a biphoton state on a superposition of three spatial modes, see Fig. 3(a) [9].

In this case, when measuring the output state under different levels of disorder (0%, 20% and 40% in Figs. 3(b-d), respectively) we do observe significant variations at the output. This is because the multimode entanglement involves modes of non-topological nature which are not robust against disorder. The biphotons tend to populate the topological mode more strongly in the presence of disorder, in other words, the weight of the topological mode in the spatial entanglement increases.

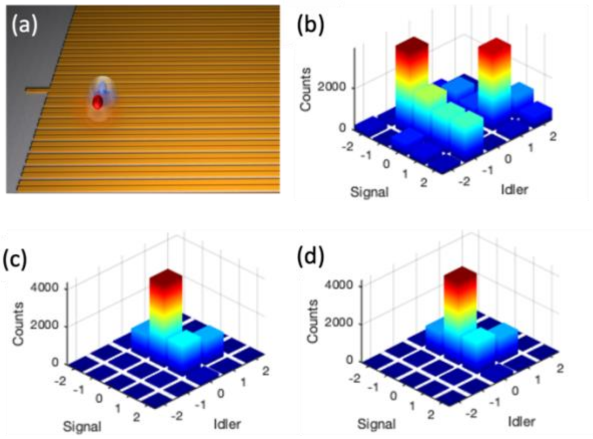

Fig. 3. (a) Silicon photonics lattice with short-short defect; (b-d) Biphoton correlation at the output of the lattice for 0%, 20% and 40% disorder in the coupling.

3. Conclusions

We have seen that topology can offer protection of certain spatial features of the biphoton correlation map, as well as of spatial entanglement, under specific kinds of disorder. We have also seen how biphoton entanglement can be induced across modes of different topology and how that leads to interesting dynamics in the presence of disorder.

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