Strong Spectral Entanglement in Spontaneous Parametric Down-Conversion

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Abstract: Photon pairs with a high degree of spectral entanglement have a very large capacity for carrying information. We describe methods for generating this type of entanglement and discuss applications.
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Spontaneous parametric down-conversion (SPDC) has proven to be a reliable source of photon pairs for a variety of quantum information applications. In most cases, the SPDC sources are configured for either polarization or time-bin entanglement. However, entanglement may also exist in auxiliary degrees of freedom, such as the photons' energies or momenta. As with polarization or time-bin entanglement, these entanglements can also carry information, often with unwanted consequences. For example, asymmetric spectral information has been shown to reduce the visibility in two-photon Hong-Ou-Mandel interference [1]; and for a broad class of multi-photon experiments, results are best in the absence of spectral entanglement [2]. In these cases, the auxiliary entanglement carries information that distinguishes between interference terms, thus diminishing the interference effect. For this reason, the elimination of auxiliary entanglements has been the subject of several recent works [3]. However, the effects of spectral and/or spatial entanglement are not always harmful and can, in fact, serve as an important resource in quantum information applications. Here, we describe an SPDC source that has been engineered for a high degree of spectral entanglement and we discuss two applications that exploit this type of entanglement.

The general expression for a two-photon state entangled in a continuous degree of freedom (like energy or momentum) is

$$|\psi\rangle = \iint dx dx' f(x,x') |x\rangle |x'\rangle, \tag{1}$$

where $|x\rangle$ and $|x'\rangle$ are single-photon states for which variable of interest has values x and x', respectively. Everything about the entanglement and about the information content is contained in the two-photon probability amplitude, $f(x,x')$. If $f(x,x')$ is separable, *i.e.*, if it can be written as the product of two independent functions, $f(x,x') = f_1(x) f_2(x')$, then the state is not entangled, since it can be expressed as the product of two independent single-photon states. In this case, x and x' are completely uncorrelated and measurement of one provides no information about the other. At the other extreme is the perfectly entangled state, for which $f(x,x') \to \delta(x - x')$. When the entanglement takes this form, then knowledge of x unambiguously identifies x'. This suggests that the information content is related to the degree of entanglement, *i.e.*, a highly entangled state carries more information.

A high degree of spectral entanglement can be attained by exploiting conservation of energy—SPDC naturally produces photons over a broad range of wavelengths. But if the process is pumped by a narrow-band laser, then conservation of energy restricts the output to only those photon pairs whose energies sum to the pump photon energy. This results in a one-to-one wavelength correspondence that approximates the delta-function correlation given above. It follows that the entanglement is strongest when the pump bandwidth is much smaller than the SPDC bandwidth. The latter is determined by the dispersive properties of the SPDC material and tends to be larger for type-I SPDC than for type-II. In particular, the bandwidth can be quite large for type-I SPDC at longer wavelengths, where materials are typically less dispersive. As an example, the plot in Fig. 1 shows the calculated joint spectrum for SPDC from a 30-mm periodically poled potassium titanyl phosphate (PPKTP) crystal that is phase-matched for degenerate type-0 down-conversion (all polarizations are the same) of a 782 nm pump. The primary advantage of the longer wavelengths is that very large bandwidths (~200 nm in this case) can be generated, which means that a high degree of entanglement can be attained, even with pulsed pumping. For this calculation, the pump duration was taken to be 1.5 ps. Stronger entanglement can be achieved by reducing the pump bandwidth and/or by using a shorter crystal.

The high degree of spectral entanglement evident in this type of state has a tremendous information-carrying capacity that can be exploited in a number of different ways. For example, a wavelength division multiplexing scheme can be employed to route photons to different parties in a quantum communication network. Because of the

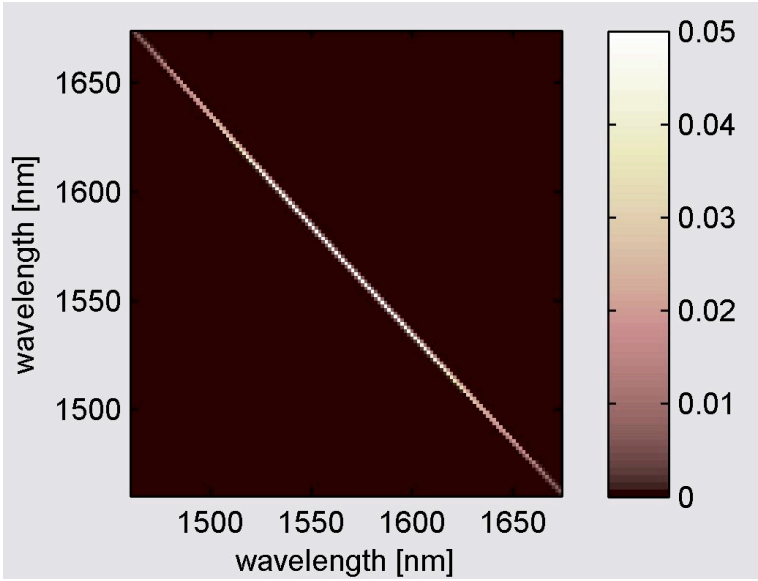

Fig. 1. Calculated joint spectrum for 30-mm PPKTP pumped by 1.5 ps pulse at 782 nm.

strong spectral correlations, each user would be "linked" only to the user with the conjugate wavelength. In this way, a single SPDC source could support dozens or perhaps hundreds of users simultaneously. With 200 GHz channel spacing, the joint spectrum plotted in Fig. 1 can support about 60 channels with very little leakage between adjacent channels.

The spectral entanglement can be used in another way, as well. If all of the photons are sent to only two parties, say Alice and Bob, then the spectral correlations can be used to facilitate large-alphabet quantum communication. Measurements performed on Alice's photons will show them to be randomly distributed throughout the SPDC spectrum. For each measurement, however, she will know the wavelength of Bob's with very high precision. In this way, Alice and Bob can establish a shared random sequence. But in contrast to polarization or time bin entanglement, the spectral entanglement will provide significantly more information per photon pair, ~6 bits in the example given here.

A similar approach was taken in a recent work by Ali-Khan *et al.*, in which temporal correlations were used for large-alphabet QKD [4]. In that work, the QKD security was established by monitoring the visibility in a conventional Franson interferometer. If, as we describe here, the spectral correlations are used to carry the large alphabet, then it follows that security must be monitored in the temporal domain. In principle, this could be done by measuring the temporal correlations. However, the large SPDC bandwidth in the example here suggests that conventional detectors would be far too slow. Alternatively, the temporal correlations could be monitored with a spectral-shift analog of the Franson interferometer. In the spectral shift Franson interferometer, Alice interferes her photon with a spectrally shifted version of itself, and Bob does the same. Bob's spectral shift, which could be accomplished with an electrooptic modulator, would be the same size as Alice's, but with opposite sign. Alice and Bob then measure the energies of their respective photons. In this scheme, there are two ways that the measured energies could sum to the pump energy: Bob could measure a blue-shifted photon and Alice could measure a red-shifted photon; or they could both measure unshifted photons. The visibility of the interference between these two possibilities is sufficient to test for the presence of eavesdroppers.

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