Schemes for fibre-based entanglement generation in the telecom band

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Abstract. We investigate schemes for generating polarization-entangled photon pairs in standard optical fibres. The advantages of a double-loop scheme are explored through comparison with two other schemes, namely, the Sagnac-loop scheme and the counter-propagating scheme. Experimental measurements with the double-loop scheme verify the predicted advantages.

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1. Introduction

The nascent field of quantum information science (QIS) has attracted a great deal of attention in recent years [1]. Multi-disciplinary research activities, drawn from fields as diverse as mathematics, physics and computer science, are propelling the advancement of QIS at an amazing speed. One of the holy grails of QIS is to make a quantum computer, which holds the promise of making classically intractable problems easily solvable [2]. Entanglement, the quintessential feature of quantum mechanics, is one of the fundamental building blocks that make a quantum computer functional. It is, therefore, essential to develop a robust, easy-to-use, integrable and networkable entanglement source. In the realm of photonic polarization-entanglement sources, two leading technological rivals exist: spontaneous parametric down-conversion (SPDC) in second-order ($\chi^{(2)}$) nonlinear crystals [3], and four-wave mixing (FWM) in third-order ($\chi^{(3)}$) nonlinear media such as standard optical fibres [4]–[6]. Despite its many advantages, a crystal-based source suffers high coupling loss when the photon pairs are launched into optical fibres for long-distance transmission [7, 8]. This is an undesirable feature if such a source were to be used in a future fibre-based quantum network. In contrast, a fibre-based entanglement source would enjoy ‘plug-and-play’ functionality in such a network, because its photonic spatial mode is directly compatible with the transmission medium and other fibre-based phase shifters and quantum gates [9]. The downside of a fibre source—the undesirable noise photons originating from spontaneous Raman scattering (SRS)—can be kept to a minimum (e.g. by cooling the fibre) to ensure optimal operation [10, 11].

In this paper, we focus our attention on further development of the fibre-based entanglement sources in the telecom band. We note that outside of the telecom band, $\chi^{(3)}$ correlated-photon sources have been realized using photonic crystal fibres [12, 13], and the architectures discussed here can be similarly applied in those systems as well. The paper is organized as follows: in section 2, we recapitulate the essence of two different schemes for generating fibre-based entangled photon-pairs, namely, the Sagnac-loop (SL) scheme and the counter-propagating (CP) scheme. In section 3, we introduce the double-loop (DL) scheme and briefly explain its operating principles. Experimental results and a comparison of the various schemes are provided in section 4, and we conclude with a discussion in section 5.

2. Two previous schemes

2.1. The SL scheme

In figure 1, we show a simplified version of the SL scheme, which neglects most of the experimental details while putting the emphasis on the gist of the scheme. Two time-delayed, orthogonally-polarized pump pulses are launched into a piece of dispersion-shifted fibre (DSF), which is shaped as a Sagnac loop. The pump wavelength is carefully chosen to be in the anomalous-dispersion regime of the DSF, so that FWM inside the DSF would phase match [14]. In the microscopic description of FWM, two pump photons of frequency $\omega_p$ inelastically scatter through the $\chi^{(3)}$ nonlinearity of the DSF to produce two offspring photons, individually called signal (or Stokes photon, of frequency $\omega_s < \omega_p$) and idler (or anti-Stokes photon, of frequency $\omega_i > \omega_p$). FWM, being a parametric process, naturally conserves energy: $2\omega_p = \omega_s + \omega_i$. The offspring photons from the same FWM process generally share the same polarization as the pump; the probability of the cross-polarized case is at least one order of magnitude less [15]. At

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the output of the Sagnac loop, the initial time delay is removed by passing the two pulses through a piece of polarization-maintaining fibre (PMF) with proper length \( \ell \) satisfying \( \ell = \Delta v_g \tau \), where \( \tau \) is the initial time delay, and \( \Delta v_g \) is the group-velocity difference between light pulses polarized in the PMF’s principle states of polarization. At the end of the PMF, there is no way to tell, not even in principle, which pulse generates the signal/idler photon-pair in the overlapped time slot, and as a result the two probability amplitudes \( |H_s H_i\rangle \) and \( |V_s V_i\rangle \) must be added coherently to give the desired polarization-entangled state \( |H_s H_i\rangle + e^{2i\phi_p} |V_s V_i\rangle \). where \( \phi_p \) is the phase difference between the original two pump pulses.

The reason for usage of a Sagnac loop is technical rather than fundamental. As described in [16], a properly aligned (by adjusting the intra-loop fibre polarization controller (FPC)) Sagnac loop can function as a total reflector for the pump photons. In this operational mode, <0.1% of the incident pump photons get transmitted through the loop together with the signal/idler photons, and the remaining >99.9% of pump photons are reflected back. This gives at least 30 dB isolation with respect to the pump in the transmitted mode. Since typically a pump rejection ratio >100 dB is required to reliably detect the trace amount of signal/idler photon-pairs [4], we place a free-space double-grating filter (not shown in figure 1) at the output of the PMF, which provides the additional \( \simeq 75 \) dB rejection for the pump, satisfying the 100-dB requirement.

Although the SL scheme has been shown to be quite effective at producing entangled photon-pairs with high fidelity [5, 6], two relatively disadvantageous points exist that make this scheme not so attractive for real applications. The first one is the technical complexity of having to introduce a fixed amount of time delay which then needs to be precisely removed after the loop. The second one is more on the physical level, namely, about half of the generated SRS photons, which need to be minimized, still remain at the output. This is because, unlike the FWM photons, the SRS photons are almost equally likely to be copolarized or cross-polarized with respect to the pump [15, 17]. In contrast, the two schemes we are about to introduce in the next sections both have the capability of blocking the cross-polarized SRS photons

\[ \text{Figure 1. A simplified schematic of the SL scheme [5]. BS, beam-splitter; FPC, fibre polarization controller; PM, polarization-maintaining.} \]
from contaminating the entangled photon-pairs at the output. Additionally, they are easier to implement in practice.

2.2. The CP scheme

As shown in figure 2, the CP scheme [18, 19] requires one linearly-polarized pump pulse at the input (I-port). The pump is polarized at 45°, so that after passing the polarization beam-splitter (PBS), it splits into two orthogonally-polarized pulses with equal power (\(H_p\) and \(V_p\)). Each pulse has a certain probability of generating its own signal/idler photon-pair (\(|H_sH_i\rangle\) and \(|V_sV_i\rangle\)), copolarized and copropagating with that pulse. The polarization rotation induced by the DSF is compensated for by using an FPC, which is adjusted to restore the polarization of the outgoing streams of photons to the initial input value. Polarization entanglement is created when the two pump pulses together with their accompanying FWM photons are recombined at the PBS’s output port (O-port), since the two probability amplitudes must add coherently to yield \(|H_sH_i\rangle + |V_sV_i\rangle\) due to their indistinguishability. The isotropic nature of the DSF ensures automatic removal of the timing information between the two pulses at the O-port of the PBS. Thus the task of the compensating element in the SL scheme (i.e. the PMF) is accomplished in a more succinct manner. An additional important functionality of the PBS, apart from being the central element in the CP scheme, is that it blocks the cross-polarized SRS photons from exiting the O-port; nevertheless the copolarized SRS photons still survive. This is already a big improvement when compared with the SL scheme, wherein such blocking function is nonexistent.

4 Just as in the SL scheme, here we also ignore the case where both pulses undergo the FWM process during propagation in the DSF, since the associated probability is negligibly small when the pump power is low.

5 In principle it is possible to make the time delay between the two pulses in the SL scheme large enough, so that at the output of the PMF the cross-polarized SRS photons fall outside of the detection time window. However, such ‘pseudo-blocking’ functionality is difficult to implement, as it necessarily involves stabilization of an interferometer with a much longer arm difference than that in the current version.
As can be seen from figure 2, all of the pump photons emerge from the same port (O-port) together with the entangled FWM photon-pairs. This means that the 30-dB filtering advantage that a Sagnac loop provides is not present in this scheme. Consequently, all of the required >100-dB pump isolation has to be realized by adding external filters, which inevitably causes a considerable amount of loss to the production rate of the entangled photon-pairs. The absence of a Sagnac loop in the CP scheme also causes self-phase modulation (SPM) of the pump to interfere with the single-counts measurements. Without the Sagnac loop, the signal/idler single counts typically exhibit a slight sinusoidal variation with the same period as the classical interference produced by pump leakage. This happens when the signal/idler detuning is small and/or the pump power is large, even when sufficient external filtering has been implemented [17, 20]. The cause is SPM-induced spectral broadening of the pump, which results in photons of the broadened pump field to pass through the filters set at the signal/idler wavelengths.

3. The DL scheme

In this section, we describe a new scheme that is capable of combining the benefits of the previous two schemes. This new scheme is dubbed DL scheme, due to the topological fact that there are two loops intertwined with each other, namely, a PBS loop and a Sagnac loop (see figure 3). Upon careful examination, the DL scheme can be viewed as a perfect combination of the SL and CP schemes. On one hand, the Sagnac loop in the DL scheme performs exactly the same way as in the SL scheme, which is to provide pump isolation of around 30 dB. On the other hand, the DL scheme is just a modified CP scheme, with the Sagnac loop replacing the straight-fibre configuration. The strengths of both the SL and CP schemes are successfully retained in the DL scheme, namely, ≃30-dB built-in filtering capability, easy implementation of a CP-like configuration and suppression of the cross-polarized SRS photons, as well as the pump-SPM-generated photons. We have summarized the above comparison among the three schemes in table 1.
Table 1. Comparison among the three schemes. Check marks denote favourable attributes of a particular scheme.

| Attribute                              | SL | CP | DL |
|----------------------------------------|----|----|----|
| Easy implementation                    | ✓  | ✓  |    |
| Blocking of cross-polarized Raman photons | ✓  | ✓  |    |
| Suppression of pump-SPM photons         | ✓  | ✓  |    |
| Inherent 30-dB filtering               | ✓  | ✓  |    |

Detailed theoretical analysis of the DL scheme’s operating principle was published in our previous work [20]. Here, we present a more intuitive approach before describing the experimental implementation. Just like in the CP scheme, the 45°-polarized pump pulse splits into two equally-powered, orthogonally-polarized components after entering the main loop—the PBS loop (see figure 3). The secondary loop, the Sagnac loop, is configured as a total reflector for both clockwise and counter-clockwise pumps. In this configuration, >99.9% of each pump pulse is reflected back to its original entrance port (1 → 1, 2 → 2), while <0.1% of each pump pulse together with its copolarized FWM-generated photon-pair gets transmitted (1 → 2, 2 → 1). The FPCs (FPC1 and FPC2) are adjusted such that the following criteria are satisfied.

1. The reflected pump photons maintain their original polarization after their individual round trip (V-port \(\text{FPC1} \rightarrow \text{Sagnac} \rightarrow \text{FPC1} \rightarrow \text{V-port} \), H-port \(\text{FPC1} \rightarrow \text{Sagnac} \rightarrow \text{FPC1} \rightarrow \text{H-port} \)).

2. The transmitted FWM-generated photons, together with the accompanying copolarized pump leakages, regain the initial input polarization after traversing the entire loop (V-port \(\text{FPC1} \rightarrow 1 \rightarrow \text{Sagnac} \rightarrow 2 \rightarrow \text{FPC2} \rightarrow \text{H-port} \), H-port \(\text{FPC1} \rightarrow 2 \rightarrow \text{Sagnac} \rightarrow 1 \rightarrow \text{FPC2} \rightarrow \text{V-port} \)).

The first criterion is satisfied when all the Sagnac-reflected pump photons go back to the I-port (the input port in figure 3) of the PBS. The second criterion is satisfied when all the Sagnac-transmitted photons exit from the O-port of the PBS. Due to indistinguishability of the clockwise and counter-clockwise paths, the two coherent FWM-photon amplitudes are thus maximally added to create the desired polarization entanglement, \(|H, H_i⟩ + |V, V_i⟩\), with maximum pump isolation provided by the Sagnac loop. The above seemingly demanding operating conditions were theoretically shown to be feasible in [20]. Experimentally, however, it turns out that the first operating criterion can be relatively relaxed without sacrificing the performance of the DL scheme. This is due to the non-overlapping time slots that the transmitted and reflected pump pulses can be made to occupy when exiting the PBS’s O-port. To be more precise, let’s denote the light propagation length (including the free space as well as the fibre) from the PBS’s I-port to port 1 of the Sagnac loop \(\ell_1\), the Sagnac-loop length \(L_s\), and the light propagation length from port 2 to O-port \(\ell_2\). The reflected pulse in the clockwise direction travels a distance of \(2\ell_1 + L_s\), whereas its counterpart in the counter-clockwise direction travels a distance of \(2\ell_2 + L_s\). In contrast, the transmitted pulses in both directions traverse the same distance \(\ell_1 + L_s + \ell_2\). The pulses’ exit-time difference, proportional to their propagation length difference, is thus given by \(\Delta t_{\pm} = \pm(\ell_1 - \ell_2)/c\), where the central (or reference) time slot is the overlapping time slot for the transmitted FWM photons. As can be clearly seen from the above expression for \(\Delta t_{\pm}\), we can judiciously choose the propagation length difference to
be large enough that the leakage photons from the two reflected pump pulses fall outside the detection-time window for the transmitted photons. This essentially means that even though the first operating criterion may not be satisfied, or a real-life PBS may deviate from its ideal performance, the feasibility of the DL scheme is not sacrificed as long as we choose a suitably long $\Delta t_{\pm}$.

The reader may wonder whether the relative phase between the PBS and the coupler of the Sagnac loop affects the attainable maximally-entangled Bell state. However, one can show that this phase is of no consequence to the quality of the obtained Bell state. The two counter-propagating FWM amplitudes (transmitted by the Sagnac loop) traverse exactly the same path on their way to being recombined at the PBS; therefore, any common phase between them is factored out. The abovementioned phase could affect the phases of the Sagnac-reflected pump pulses, but they are of no interest to us since they are outside the detection time window.

4. Experiments and results

A detailed layout of the experimental implementation of the DL scheme is shown in figure 4. In the experiment, a Ti-sapphire laser pumped optical parametric oscillator (OPO) is used as the pump source. We only select a small part of its broad spectrum, by first dispersing the OPO output using a grating ($G_1$) and then coupling the spatially dispersed light into a single-mode fibre. The resulting pump spectrum has a central wavelength of 1552.09 nm, which is selected to match the zero-dispersion wavelength of the DSF in order to facilitate the phase-matched FWM
process, and a full-width at half-maximum (FWHM) of 0.8 nm (pulse width $\simeq 5$ ps), which is determined by the optics used to couple light into the fibre. The pump then passes through an erbium-doped fibre amplifier (EDFA) to achieve the desired pump power. Out-of-band amplified spontaneous emission from the EDFA is suppressed by passing the pump through a 1-nm-bandwidth tunable filter (Newport, model TBF-1550-1.0). A fused-silica 95/5 coupler is used to direct 5% of the pump to a meter for monitoring the pump power and stability. The remaining 95% of the pump is coupled back into free space. It passes through several free-space optical elements before entering the main loop of the DL scheme (the central PBS in the DL scheme is labelled PBS$_3$ in figure 4). Among those free-space optical elements are HWP$_1$, QWP$_1$, PBS$_1$ and HWP$_2$, which are used to adjust the pump to be 45$^\circ$ linearly polarized. The pump then passes through a polarization Michelson interferometer (PMI, consisting of PBS$_2$, QWP$_2$, QWP$_3$ and the mirrors placed behind them), which splits the pump to have two orthogonally polarized, equally powered, relatively delayed components ($H_p$ and $V_p$). A piezoelectric transducer (PZT) is placed behind one of the PMI mirrors to provide stepwise phase variability between the two pump components. HWP$_3$ is taken out for the phase-scan experiment (or equivalently, it is set such that no polarization rotation is induced), but is put back for the fixed-phase experiment. The pumps then enter the DL scheme’s main loop. We find it more convenient in practice to use free-space waveplates (HWP$_4$, $5$ and QWP$_4$, $5$) than FPCs, as the former have negligible transmission loss and are more accurate in controlling polarization. A 500 m-long DSF with a zero-dispersion wavelength of around 1552 nm is used in the experiment. Together with an FPC and a 50/50 coupler, it constitutes the Sagnac-loop part of the DL scheme. $\Delta \tau_{\pm}$ for the implemented DL scheme is chosen to be $\pm 7.7$ ns, which is large enough for our detectors to gate out, and yet different enough from the laser’s repetition period (13.2 ns). The output from the DL scheme is sent through a double-grating filter to achieve the desired pump isolation ($\gg 100$ dB). Two sets of polarization analysers (PAs; PA$_1$ consists of HWP$_7$ and PBS$_4$, whereas PA$_2$ consists of HWP$_8$ and PBS$_5$) are constructed, and individually inserted in the signal (1557.09 nm) and idler (1547.12 nm) channels, respectively. Single-channel counts, as well as coincidence counts between the two channels, are recorded by two avalanche photodiodes (APD$_1$ and APD$_2$) operated in the gated Geiger mode. The detection results are further analysed by a ‘coincidence counter’ software. In the experiment, the typical generation rate is $2 \times 10^{-3}$ photon pairs/pulse at the SL output, and the total propagation loss from the DL output to the detection system is about 3 dB.

Figure 5 shows the experimentally measured single counts and coincidence counts, when both PA-angles are set to be 45$^\circ$ (HWP angles are 22.5$^\circ$) and we scan the relative phase $\phi_p$ between the two orthogonally-polarized pump pulses using the PZT. We observe very stable and constant single counts for both the signal and idler channels, and coincidence counts that exhibit the so-called two-photon interference (TPI) with good visibility ($\sim 92\%$). We note that the detector dark-count contributions have been subtracted out from all the results shown in this paper. The relatively large error-bars associated with the TPI data points can be attributed to the low data-collection rate, which can be improved by either counting for a longer time (here we count for only 20 s), or using faster electronics [21].

In figure 6, we show similar results (nearly constant single counts and TPI with $\sim 92\%$ visibility), but this time we fix $\phi_p$ to be 0 (by blocking one arm in the PMI, putting in HWP$_3$ and setting it to 22.5$^\circ$) and scan the relative angle $\Delta \theta$ between the two HWPs in the PAs$^6$. This

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$^6$ We note here that the data was taken for various settings of one HWP while the angle of the other half-wave plate was relatively varied.
Figure 5. Single counts as well as TPI as a function of the relative phase $\phi_p$ between the two pump pulses.

Figure 6. Single counts as well as TPI as a function of the relative angle $\Delta \theta$ between the two HWPs in the PAs.

Observation further confirms the polarization-entangled nature of the DL source. Both of the above results are obtained with a total average pump power (measured before PBS$_3$) of around 380 $\mu$W, which has two equally-powered components ($P_H = P_V \simeq 190 \mu$W).

In order to demonstrate the claimed 30-dB filtering advantage over the CP scheme, we set the FPC inside the Sagnac loop in such a way that the loop becomes totally transmissive. In this configuration, the DL scheme reduces to the CP scheme, because the former’s secondary loop—the Sagnac loop—now functions equivalent to a piece of straight fibre. We then record the single counts, coincidence counts (CC), as well as accidental coincidence counts (ACC, which are...
coincidence counts between adjacent pulses \([4, 5]\)) as we vary \(\Delta \theta\). Figure 7 depicts the results of such an experiment. As shown, no visible TPI is observed under these operating conditions. This is because the \(\simeq 75\)-dB isolation for the pump that is provided by the double-grating filter is not enough to adequately suppress the pump photons without the additional 30-dB filtering provided by a totally-reflective Sagnac loop. Indeed, there is virtually no difference between the CC and the ACC, both of which follow the shape given by the product of the measured single counts. Such behaviour shows that in this case the majority of the detected photons are pump-leakage photons, since the detected signal counts (the channel in which the HWP is rotated) peak at \(\Delta \theta \simeq 45^\circ\), which is the polarization of the input pump. Therefore, comparing the results shown in figure 6, which is obtained under the DL operating conditions, with those in figure 7, we can justifiably claim the existence of the filtering advantage provided by the DL scheme.

5. Conclusion

We have demonstrated that a novel double-loop scheme successfully combines the benefits of the previously implemented SL and CP schemes while avoiding their disadvantages. The demonstration of the DL scheme is performed in free space as a proof-of-principle experiment. It is foreseeable that an all-fibre version of the DL scheme can be carried out with commercially available fibre-coupled components. Cooling the fibre to liquid nitrogen temperature will also improve the purity of the generated entanglement (and thus the TPI visibility), as the SRS photons are suppressed when the temperature drops \([10, 11]\).

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