Chapter 7
Conclusion

It was first proposed in 2002 by Migdall et al. [1] that a pseudo-deterministic source of heralded single photons could be realised by active multiplexing. In the intervening years, this work has been built upon with the development of several other novel multiplexing protocols in a variety of domains. Of these protocols, a limited number of multiplexed devices have been constructed, but none so far have achieved this with the heralded pure single photon states required by many quantum information science applications. The work presented in this thesis builds upon a broad foundation of previous work in a range of fields, including photon-pair generation in photonic crystal fibres, spectral engineering of the two-photon state and multiplexing strategies, to demonstrate an active multiplexed source of heralded single photons in pure spectral states. How this source fits into the landscape of multiplexed sources can be seen in Table 7.1, where it is highlighted in blue. Overall, the performance of the multiplexed source is comparable to previous sources, outperforming many systems of similar multiplexing depth whilst doing so in an integrated architecture that is stable, scalable, portable, and user-friendly.

7.1 Summary

In Chap. 1, the motivation for developing a deterministic source of pure indistinguishable heralded single photons was discussed. The properties required of these photons and the demands this places on source technology were outlined. Chapter 2 developed the theory of photon pair generation via four-wave mixing in photonic crystal fibres, introducing the concept of phasematching through which photons in the pair may become spectrally correlated. Following this, a method of spectrally engineering the two-photon state to remove these correlations was detailed. This was

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Table 7.1 Multiplexing scheme performance comparison. Medium = pair generation process and nonlinear material. Multiplexed = implemented multiplexing scheme (S = spatial, T = temporal). Depth = number of multiplexed bins, or stages used. Pure State = spectral engineering carried out. $g^{(2)}(0)$ = second order coherence measurement. C.R. = count rate or brightness. Rep. rate = maximum switching rate. The system outlined in this Thesis is shown highlighted in blue for comparison

Year	Paper	Medium	Multiplexed	Depth	Purity	$g^{(2)}(0)$	C.R.	Rep. Rate
2002	Pittman [2]	PDC in BBO	Storage Loop (T)	5	–	–	2 C/s	75 MHz
2004	Jeffery [3]	PDC in BBO	Storage Loop (T)	–	–	–	–	10–50 kHz
2011	Ma [4]	PDC in BBO	Log-Tree (S)	4	–	0.08	714 C/s	~ 15 MHz
2011	Broome [5]	PDC in BBO	Pulse Doubling (T)	2	–	–	40 C/s/mW	152 MHz
2013	Collins [6]	FWM in PhCW	Log-Tree (S)	2	–	~0.19	1–5 C/s	1 MHz
2014	Meany [7]	PDC in PPLNW	Log-Tree (S)	4	–	–	60–70 C/s	1 MHz
2015	Kaneda [8]	PDC in BiBO	Storage Loop (T)	35	0.05	0.479	19.3 kC/s	50 kHz
2016	Mendoza [9]	PDC in PPLN	Tree + Delay (S and T)	2 and 4	–	–	140 C/s	500 KHz
2016	Xiong [10]	FWM in Nanowire	Delay Lines (T)	4	69–91%	–	600 C/s	10 MHz
2016	This Thesis	FWM in PCF	Log-Tree (S)	2	70–86%	0.05	100 C/s	1 MHz

achieved by group-velocity matching the pump, signal, and idler field in a method laid out by Grice and Walmsley [11] and Garay-Palmett et al. [12]. The Schmidt decomposition technique was introduced as a means of quantifying the degree of spectral correlations within the two-photon joint spectral amplitude. From this the approximate purity of the heralded single photon was determined using the singular value decomposition. Factors affecting the photon number statistics of the heralded single photon were discussed, and the second order coherence function was introduced as a method for measuring the photon number statistics.

In Chap. 3, the theory behind active multiplexing in the spatial and temporal domain was introduced. The performance of these multiplexed sources is largely influenced by the loss of the constituent components. To determine the effect of loss, a numerical model of the photon pair generation process and multiplexing strategy was established. Within this model, systems consisting of different numbers of photon pair sources were considered with different levels of loss. It was found that in the spatial domain, when the loss of the switch is high, it is no longer beneficial to increase the multiplexing depth, even though the probability of heralding a pair increases. Increasing the multiplexing depth becomes detrimental, resulting in a reduction in the probability of delivering a single photon from the output, due to a reduction in the fidelity of the heralded single photon state by reintroduction of the vacuum. In the temporal domain, there is no such detrimental effect by "over-multiplexing", instead the performance of the source becomes dominated by only a handful of temporal modes which have experienced the least amount of loss. A comparison between temporal and spatial multiplexing was made, from which it was seen that temporal multiplexing is more efficient in terms of the number of experimental resources required.

Chapter 4 documented the design, fabrication, and characterisation of photonic crystal fibres for photon pair generation and more specifically photons heralded into a spectrally engineered pure state. The technique of stimulated emission tomography was introduced as a means of measuring the joint spectral distribution function of the two-photon state. From these measurements, an upper bound was placed on the purity of the heralded idler photon of $\sim$86%. Stimulated emission tomography was also used to estimate the length scale over which the PCF yields homogeneous regions of phasematching, this was found to be roughly $\sim$30 cm. Lengths longer that this typically contained multiple regions of different dispersion, resulting in fluctuations in the FWM wavelengths and additional spectral correlations along the length of the fibre.

Chapter 5 details the construction of two photon pair sources in an integrated fibre architecture, using two pieces of PCF which were identified as having factorable joint spectral distributions from the SET measurements in Chap. 4. A novel, broadband spectral filter was developed in a photonic bandgap fibre. This allowed the amount of noise in the system to be reduced without impacting on the spectrally engineered JSI, unlike previous implementations of fibre based sources which made use of narrowband FBGs. Each source was characterised in the classical domain, including measurements of the loss of 5.6 dB at 810 nm and 5.0 dB at 1550 nm, not including the switch loss of approximately 1dB. The process of switch integration to multiplex the two sources was outlined.

In Chap. 6, each individual source and the complete multiplexed device was characterised. This included measurement of the coincidence count rates between the signal and idler modes. From this, at a coincidence to accidentals ratio of 39.8, an improvement factor of 86% was found on multiplexing the two sources together. Following this, the marginal second order coherence was measured to determine the spectral purity of the heralded single photon state. This allowed a comparison with the SET measurements of Chap. 4. Both sources displayed a $g_m^{(2)}(0) = 1.7$, corresponding to a heralded state purity of 70%.

Finally a violation of the classical bound of the heralded second-order coherence was observed for both individual sources and the complete multiplexed device. This indicated that single photon states were indeed being generated by the systems. A minimum value of $g_H^{(2)}(0) = 0.049 \pm 0.02$ at a coincidence count rate of 100 ± 10

C/s was recorded for the multiplexed device. Unlike previous systems, this multiplexed device is capable of producing high quality single photon states at count rates similar or greater than previous implementations. This demonstrates a step forward in multiplexed source technology.

7.2 Future Outlook

7.2.1 Photon Pair Generation in Fibres

The photon pair sources demonstrated in this thesis have several novel features that could yield further performance enhancement if optimised further. Firstly, the phasematching scheme implemented to give group-velocity matched solutions far from the pump was selected to work with a relatively inexpensive laser system. The output pulses from the laser have a significant amount of SPM on them; this will limit the spectral and temporal purity of the heralded state. The fibre structure that yields this phasematching is quite sensitive to imperfections in the fabrication process. Improving the fibre drawing process, particularly to reduce the sensitivity to small changes in the structure, would be beneficial. This could be achieved by working at a higher draw tension to minimise these fluctuations. If this were successful then the fibre would be homogeneous over a longer length, allowing longer pieces of fibre to be used. As the probability of generating a pair scales with the square of fibre length, this would lead to higher count rates.

Secondly, the use of photonic bandgap fibre as a broadband filter was demonstrated to be successful, but at the expense of approximately 3dB of loss per filter. Further work on minimising the insertion loss of this component, as well as reducing the bend loss, which currently limits the footprint of the source to $80\,\mathrm{cm} \times 45\,\mathrm{cm} \times 8\,\mathrm{cm}$, would be of significant benefit. A photograph of the two complete sources is shown in Fig. 7.1. An alternative, and perhaps more elegant route would be to try to achieve photon pair generation in a hybrid photonic crystal-bandgap fibre. Several groups [13, 14] have implemented a hybrid fibre structure whose cross-sectional profile consists of an array of high-index rods to achieve a photonic bandgap, whilst a secondary array of air holes in the interstitial sites could be used to tune the dispersion. These air holes also reduce the bend loss of the fibre by increasing the refractive index contrast between the guided mode of the core and the cladding supermodes [15]. This would in theory allow photon pair generation with very little Raman noise. This would solve one of the largest deficits of fibre based photon pair sources.

The bandgap portion of the cladding leads to the formation of regions of high and low transmission as seen in Chap. 4. Photon pairs could be generated directly into a bandgap, whilst Raman shifted pump light becomes trapped in the bandgap in which the pump propagates due to the high loss region separating the pump from the idler. It still waits to be seen how much dispersion control can be exercised in these fibres,

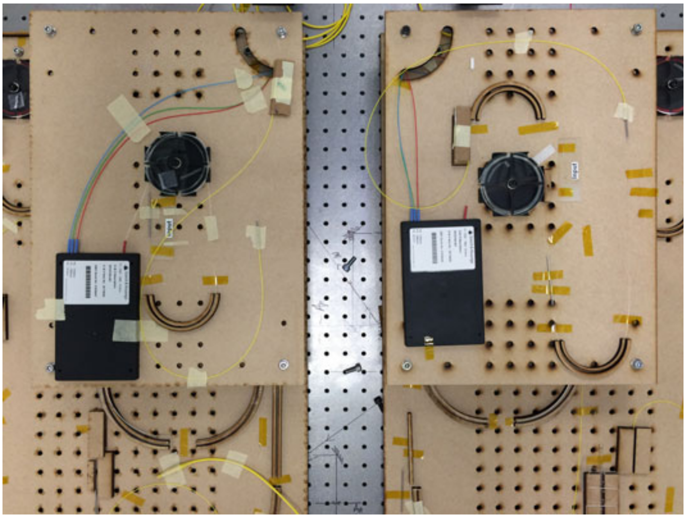

Fig. 7.1 A photograph of the two photon pair sources, side-by-side on the bench *top*

but if sufficient control can be made, these fibres could be a significant improvement over other fibre designs.

One key measurement that is missing from this discussion is the Hong-Ou-Mandel interference between heralded single photons from each source. This would provide a more accurate measure of the indistinguishability of the heralded photons from the multiplexed system; this aspect is still on going. A large benefit of the integrated fibre sources constructed here is the potential of replacing the current PCFs with a new design iteration, without having to alter any of the filtering or switching. One potential work package could be to replace the current fibre with birefringent PCFs for pair-generation such as those developed by McMillan et al. [16, 17]. These fibres have already been proven to yield high heralded count rates, and were designed to produce a factorable two-photon state.

7.2.2 Multiplexed Photon Pair Sources

Active multiplexing of photon pair sources is a top contender for producing a pseudo-deterministic source of single photons. In the light of the simulation results displayed in Chap. 3, optimising the collection efficiency of the photons from the source medium into the switch network, and minimising the loss of the switch network will be key. Additionally, it was seen that moving to PNR heralding detectors immediately brings significant performance enhancements. Development of high efficiency, fast PNR detectors in tandem with faster and lower loss optical switches will be key to fully realising the potential of multiplexed devices.

Poor collection efficiency can be mitigated by using more sources, but only if the switch loss is very low. Rather than the ideal 17 sources for a pseudo-deterministic source, tens of sources may be required if the loss is not improved (but this requires near perfect switches). The ability to fabricate large numbers of identical sources will be key. This is one of major the benefits of chip-scale waveguide sources. However, to minimise loss and remain an integrated device will necessitate developing switch, delay and detector technology in the host material, none of which are trivial to achieve. For the time being, fibre based sources have the potential to be scaled up to multiple sources with relative ease, especially if multiplexed in the temporal domain. For the immediate future of the sources fabricated in this thesis, moving into the temporal domain with the addition of a storage loop to the output is currently being explored.

An integrated source architecture offers many benefits over free-space implementations, primarily higher stability, portability and the potential for packaging into a commercial device. The large background in commercialisation of fibre based technology in the telecommunications industry will be highly advantageous. There are still some hurdles to overcome though. As was seen in Chap. 4, sources based on the current PCF design may be restricted by structural and dispersion fluctuations, but this could be addressed by redesigning the fibre to exploit birefringent PCF. The pitch and hole size required to achieve phasematched wavelengths of 810/1550 nm in such a scheme are much more routinely fabricated. As every length of fibre used in every source must be identical makes this difficult but not impossible to achieve, especially with the huge benefits that SET brings for characterisation.

Multiplexing in the temporal domain is well suited to fibre based sources, as the necessary storage loop can be easily fabricated in low loss single mode fibre. This also reduces the overheads in the number of identical PCF fibres required. As seen in the more recent literature [9], it is likely that some form of hybrid scheme, utilising both spatial and temporal multiplexing will prevail as a balance between performance and resource costs.

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