

Entanglement Generation and Routing in Optical Networks

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Abstract New telecom wavelength sources of polarization entangled photon pairs allow the distribution of entanglement through metro-access networks using standard equipment. This is essential to ease the deployment of future applications that can profit from quantum entanglement, such as quantum cryptography.

Introduction

Current optical infrastructure is optimized for the transmission of signals composed by a large number of photons. Regeneration of weak classic signals is facilitated through optical amplifiers that spoil any quantum signals present in the network. Moreover, non-linear effects in fiber, like Raman scattering or four-wave-mixing (FWM) have to be mitigated in order to multiplex a clean quantum channel in a modern telecommunication network, which turns out to be a difficult task when signals are made up of just one photon per qubit.

This work is a first step to close the gap between entanglement distribution and optical networks. As a starting point, we focus on the telecom network ability to route single photons with the only requirement of not introducing loss budget limitations for the quantum channel.

Recent progress in periodically-poled nonlinear optical crystals for the production of entangled photon pairs (referred to as EPR sources after Einstein, Podolsky and Rosen) at telecom wavelengths have increased production rate and quality of entanglement. Additionally, single-photon detectors have improved noticeably and are nowadays achieving high quantum efficiency and low dark count rates.

Time-bin and polarization entanglement among distant parties have been demonstrated to be technologically feasible. In particular, we have demonstrated polarization tracking in deployed fibers. Here we will concentrate in the distribution of polarization entangled pairs. Both types of entanglement need their own steering signals and this will need to be taken into account when multiplexing many quantum channels over one fiber.

The paper first presents an overview of state-of-the-art sources based on different generation processes and then we introduce network architecture suitable to send photons to different users and to select pairs of them on demand.

Photon pairs at telecom wavelength

FWM in dispersion-shifted fibers was first used to generate entangled photon pairs¹ at telecom wavelength years ago, but Raman radiation limit the quality of the entanglement. Only liquid nitrogen cooling reduced the background photons sufficiently to be usable in quantum communications. These are the only commercial sources at telecom wavelength available today². FWM in novel structures, as in SOI, can be used to generate polarization entangled photon pairs in the C-band, as demonstrated recently³. Photon pairs in the O-band⁴ have also been produced and compared to other QKD-schemes.

However, the most widespread method to generate entangled photon pairs is spontaneous parametric down-conversion (SPDC). A single pump photon can be split into a photon pair when the energy is conserved (e.g. 775nm → 1550nm/1550nm) and the phase is matched (momentum conservation). In the case of indistinguishable generation processes, the polarization of the photons from the same pair is entangled. Novel realizations of this idea have combined both generation sections in a single optical chip⁵ made out of type-II phase matched periodically of periodically poled Lithium Niobate (ppLN). In terms of conversion efficiency waveguide-based structures outperform all comparable structures by far.

SPDC is also present for type-I phase-matching, with the advantage of a relaxed phase-matching condition for ppLN around 1550nm producing an ultra-broad spectrum of a bandwidth of 70nm⁶. An even broader spectrum spanning across 8 CWDM channels (160 nm) could be generated by reducing the length of the 30mm crystals to a few mm. The high efficiency of the conversion process would not lead to pump powers larger than a few mW.

The energy conservation of the generation process ensures the photons of each pair to be

generated at optical frequencies symmetrical to the center given by degenerate SPDC. When the sources' output passes through a DWDM-demultiplexer each channel contains only photons with a related partner in a certain other channel. Independent pairs at different channels do not interact; therefore a single, sliceable source can be shared among many users⁶.

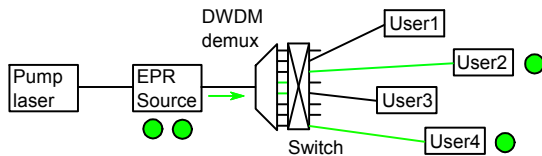


Fig. 1: The pump laser operated at a wavelength λ_p generates entangled photon pairs in the EPR-source. The photons of different pairs are separated by the DWDM-demux. An nxm-switch distributes the photon pairs to users⁶.

On-demand user selection by switching

The overall system, including the pump laser, the EPR-source and the DWDM-multiplexer is extended by an optical switch as shown in Fig. 1 in order to connect users demanding access to entanglement⁶. The switch is operated to select photon pairs in two DWDM-channels and to connect two users to them. The number of connections that can be established simultaneously is only limited by the bandwidth of the source and the output of the DWDM. The overall number of users is limited only by the number of outputs of the nxm-switch.

Centralized EPR-source for hybrid Ring+tree based metro-access networks

Ideally, a single source would be enough to distribute its pairs to all users in a metro-access network. In the following we assume a single ring-shaped backbone network and k access networks attached to it. A way to ensure full connectivity between each possible pair of users, independent of its location in the metropolitan area, is sketched in Fig. 2.

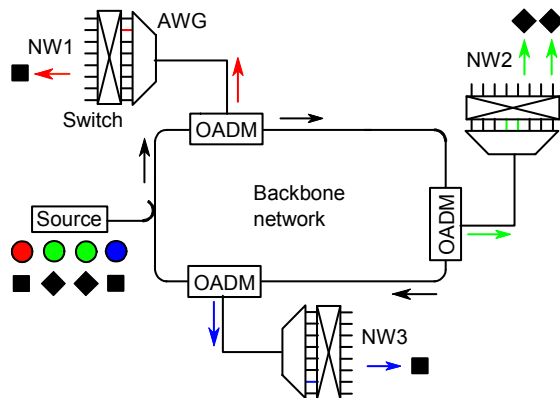


Fig. 2: The source is attached to a ring-shaped network and the photons for each access NW (NW1 to NW3 are shown) are dropped by the add/drop-mux OADM selected to the corresponding CWDM-channel. Colors mean lambdas and symbols, entanglement.

The source is connected to the ring. Each access network (NW) is associated to a specific CWDM-channel that is dropped out from the ring. A DWDM-demux slices the corresponding CWDM-channel in a finer grid. End-users are then connected over a switch array to finish the routing between different users⁷. With this architecture, the single source, as introduced in Fig. 1, needs to be extended by similar sources with slightly shifted pump wavelength, which causes a shift in the central emission wavelength. The underlying principle is shown in Fig. 3, where the leftmost diagram shows how to connect users from a single NW, the second would connect users from two adjacent NWs and the third would connect users from the first NW to the third NW, while users from the second NW can be connected among themselves.

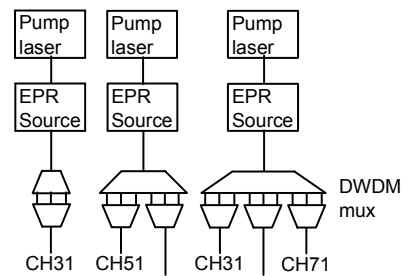


Fig. 3: Several sources pumped by different wavelengths and producing different bandwidth are needed. The DWDM-demux slices the spectrum combined by DWDM-mux to channels in CWDM wavelength ranges (CH31=1531 nm, CH51=1551, etc.).

To achieve full end-to-end connectivity between all users of k access networks, the number of sources needs to be $s = 2k - 1$. Again, a switch is required to pair all users of each access network to users from another one. Table 1 shows a channel plan for $k = 3$ access networks that achieves full connectivity between all users. A switch would select the different possibilities given in Tab. 1. As an example, if the rightmost source of Fig. 3 is selected as the source shown in Fig. 2, the connectivity is given by the 3rd and 4th row of Tab. 1. The users of NW2 would be connected among them sharing entanglement (◆), while the users of NW1 would share entanglement (■) with those of NW3.

Tab. 1: Wavelength plan for the EPR-sources. For a ring network with $k=3$ access trees, 6 different photon pair combinations are realized using 5 EPR-sources.

Wavelength	Pairs	Connectivity
$\lambda_p=765.5\text{nm}$	Ch31-Ch31	NW1 – NW1
$\lambda_p=770.5\text{nm}$	Ch31-Ch51	NW1 – NW2
$\lambda_p=775.5\text{nm}$	Ch31-Ch71	NW1 – NW3
$\lambda_p=775.5\text{nm}$	Ch51-Ch51	NW2 – NW2
$\lambda_p=780.5\text{nm}$	Ch51-Ch71	NW2 – NW3
$\lambda_p=785.5\text{nm}$	Ch71-Ch71	NW3 – NW3

Reconfigurable mesh-shaped network

In the ring based network structure shown in Fig.2 the maximum number of NW and, subsequently, the maximum number of simultaneous connections between users is bounded by: (i) the path losses due to ring topology, (ii) the fixed-mapping of CWDM channels. The ring topology fixes the path to distribute photon pairs to users in different access networks and signals must hop across all nodes in between. Hence, the maximum tolerable loss budget limits the number of nodes that can be crossed. The second limitation is related to the fact that only a limited number of CWDM channels in the spectrum experience low fiber loss during propagation and the requirements for number and spectrum of sources at higher number of NW grows linearly. In order to overcome these limitations for obtaining a scalable metro-access network, we modify the metro segment using a mesh topology instead of a ring. Reconfigurable switched nodes substitute the simple static ones (see Fig. 4). Therefore, we replace the OADMS by CWDM-based photonic cross-connects PXC. The design works as follows: The generated spectrum from a photon-pair source is demultiplexed into CWDM channels; these enter a switch matrix and are routed to their corresponding output port; before leaving the device, all signals directed towards a port are multiplexed again. The mesh topology allows deploying extra links between any pair of nodes. This permits to reconfigure the network to use the path with the lowest losses, reducing the budget that the ring network required. On the other hand, this network allows selecting the CWDM channels that are dropped at each

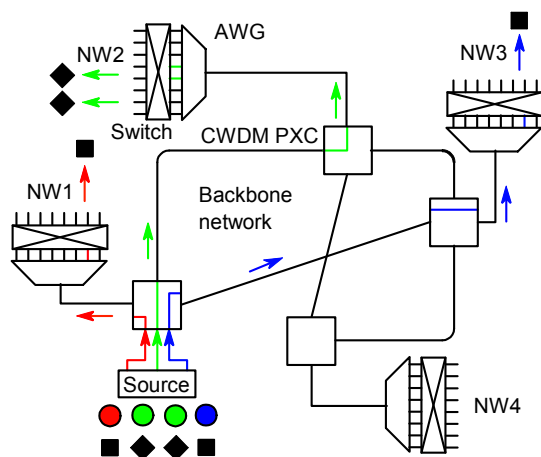


Fig. 4: The source is attached to a mesh-shaped network. A CWDM-based photonic cross-connect routes the CWDM channels (colored) to the corresponding access network (NW1-4). Entanglement sharing is represented by the symbols (squares, diamonds)

NW at a given configuration for routing. All needed pair distribution configurations are switched sequentially in flexible way for requested connectivity. For the same example as in Fig. 2 a single configuration is sufficient as shown in Fig. 4: A source with $\lambda_p=775.5\text{nm}$ generates pairs according to the wavelength plan of Tab. 1. PXCs are configured to route CH31 to NW1, CH71 to NW3 and CH51 to NW2. Users from those access networks can connect to the appropriate port using the switches. Later, PXC can be reconfigured to route those channels to other NWS. Moreover, to reduce fiber losses and add pair generation capabilities in a flexible way, additional sources of entangled photons can be installed in every PXC, thus catering for a possible grow in the number of users.

Conclusions

This work intends to bring together quantum optics and optical networks to open a new direction of research in order to enable entanglement distribution over telecom networks with a large number of users. We try to reconcile the requirements of quantum sources with standard telecommunications equipment and propose network structures supporting a high number of entanglement distribution channels.

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