# Proposal on improving the overall efficiency of entangled photon sources for Quantum Communication


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## Abstract

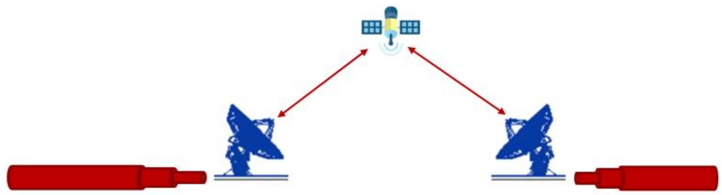
Quantum communication is promising to provide a secure way of communication or information exchange utilizing the quantum mechanics principles of superposition, quantum entanglement, no-cloning theorem to realize and develop a secure network. Security of information is the main objective that fuels the research and development in quantum communication, as is quite often challenged in classical communication. In quantum communication, to achieve and build a quantum communication network that is reliable and supports long-distance depends based on photon-pair sources.

In this paper, we discussed the different entangled photon generation sources, techniques, and arrangement. With the multiple advancements for sources provided in this literature review, we have tried to list out the process and suggest collective ways to achieve an efficient process. It involves combining entanglement photon generation with SPDC in Rydberg atoms along with heralded photons that when embedded in nanoantenna provide a deterministic photon pair with high collection efficiency in turn resulting in bright photon-pair sources. Further in this paper, we provide the probable ways to efficiently couple the source with optical infrastructure at the telecom band and suggest different arrangements of the source operating at different bands. A photon-pair source, one at visible and the other at telecom band generated using the SFWM process employed at the source end, provides efficient coupling and local connectivity to quantum systems. At the same time, we suggest an arrangement of having multiple less efficient telecom band photon sources used, to realize the robust, high-speed quantum communication.


## Introduction

With a photon pair source employing different characteristics of pair generation techniques holds promise for designing networks that not only supports local quantum networks but also long-distance communication, utilizing existing optical fibers infrastructure. Currently this achievement is either available in labs or in the testbed not on a practical scale involving different stakeholders. For a quantum communication that is feasible and scalable to a full-scale quantum network, it is required that all basic blocks of networks such as photon pair sources, quantum channel, repeaters, detectors work effectively and matches speed of data transfer as compared to classical communication.

Along with technological challenges, there is need, requirement and constraints imposed on the research and development of quantum communication to utilize the existing communication infrastructure i.e., optical fiber cables for long distance quantum communication and free space that will act as a bridge between quantum optical fiber communication (Report [1]).



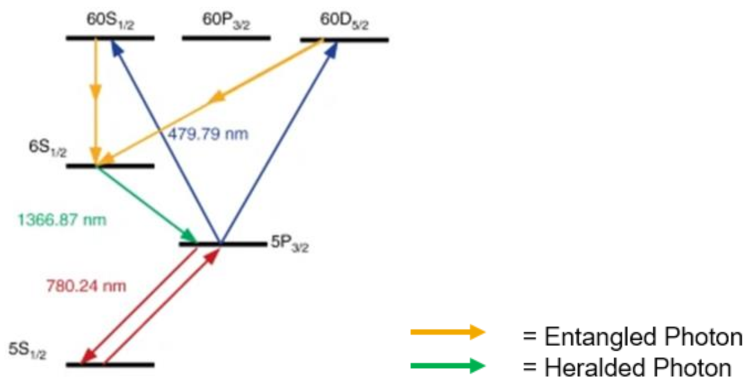
When it comes to addressing the design of a high-speed network, it narrows down to have a photon pairs source that can produce entanglement at a very fast rate, with the source compatible with the channel causing minimal change in existing infrastructure. Since, source is the component where the promise of secure communication resides, we have identified the three key areas to focus the ongoing improvements related to Quantum Communication source that includes generation of entangled photon for communication, rate and collection efficiency of the generated entangled photons, the coupling efficiency of photons with the medium of transmission that would need to be addressed to support reliable and efficient network.

Unlike classical communication, in quantum communication generation of entangled photons process needs to be deterministic, so that the sender can utilize it in measurement and communication. But to achieve a deterministic entangled photon, it is often the case that the quantum state of the photon ends up being measured or reducing the overall efficiency of the source. Using a trigger photon generation to ensure the entangled photon, reduces overall efficiency in terms of the brightness of entangled photons. Complex spatial distribution and broad spectral width of an entangled photon led to the low collection efficiency of generated photons, that further leads to the low generation rate of the entangled photons, even in case of bright, high-rate entangled photons. Utilization of existing optical fiber infrastructure requires to have a source that generates photons in telecom bands, to have low attenuation, easy coupling and ensuring long-distance communication. The broad emission spectrum of the entangled photon leads to low coupling efficiency with the optical channel. Utilizing optical cavities for spectral filtering or having very narrow bandpass filters reduces the number of entangled photons for the telecom band, which in turn reduces the overall efficiency of the source.

## Generation of Entangled photon for communication.

Entangled photons are required for wide applications such as quantum teleportation, quantum computation, quantum information transfer. A compact source of entangled photon which can be used in integrated platform utilizes SPDC process in nonlinear crystal. It employs pump photons for this process which interacts with a quantum field inside medium generating photon pairs with down conversion.
Apart from the efficiency and emission of entangled photon source, another major required quality is the deterministic generation of entangled photon generation is heralding, confirming photon pair generation without measuring it. In the conventional SPDC method, this is achieved by simultaneous emission of a photon along with entangled pairs, called trigger photons which are used for heralding but at the cost efficiency of entangled pair generation and other way to confirm photon pair generation is by measuring it. Generation of deterministic entangled photon is achieved by two-photon spontaneous emission in Rydberg atoms and further emission of heralding photon [1].
In this method [1], atoms are prepared to be in Rydberg state especially in optical cavity with cavity frequency matching transition frequency of first emission to support two emissions (entangled photon and further heralded photon) before reaching to ground state.
This scheme [1] is achieved in rubidium atoms with excited Rydberg state 60S1/2 using 780nm wavelength probe field and 479.49nm wavelength control field and has lifetime of 100us. Atom from the excited state

of 60S1/2 decays to 5P3/2 emitting entangle photon pairs and heralding photon which includes two-stage transition i.e., 60s1/2 state to 6S1/2 generating entangled pairs and 6S1/2 to 5P3/2 generating heralded photon of 1367nm instantaneously after entangled pair which helps to confirm the generation of entangled photon pairs without measuring it. After this complete state transition, the process is repeated exciting atom to Rydberg state, and the process continues.



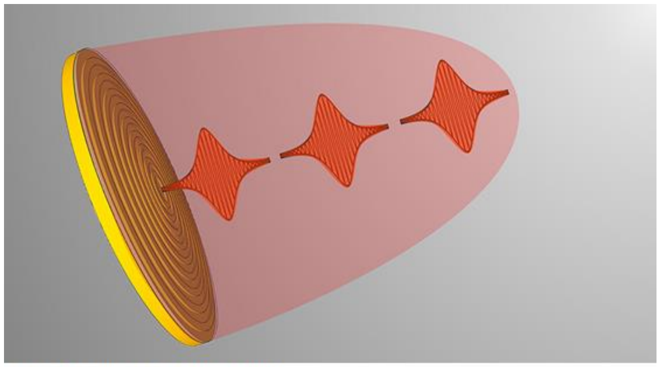
[1]

## Rate and collection efficiency of the generated entangled photons.

The collection rate of the generated entangled photons from the source ensures the availability of an increased number of entangled photons. This needs a method to direct the spatially distributed photons in the required direction. One mechanism [2] is to employ nano-antenna as a source of the entangled photon embedded in nano-antenna with a single-photon source. When the source producing single photons is placed precisely in the middle of the designed antenna, to increase the collection efficiency to reach efficiency around 85%.

It is required that device design can be scalable, works at room temperature, and provide high collection efficiency. template stripping was used for fabricating ultrasmooth 'Hybrid metal-dielectric bullseye nanoantenna' [2]. Challenges in coupling of Emitter-nanoantenna, placing emitter well-centered at bullseye. It employs, atomic force microscopy (AFM) probe that scans the region for writing, with probe tip wetted with a QD-solvent suspension (the “ink”) and a droplet is placed in the predetermined location by contacting the AFM tip to the substrate. Nano-pipette delivers Quantum dot solutions or photon sources at the center of the bullseye in the dielectric medium at the required height and distance from metal to avoid metal-induced losses. The dielectric medium acts as a waveguide providing a path for emitted light radially outward from circular gratings. The tuning of the antenna keeps the diffracted waves interference at low angles, resulting in a highly directional photon stream.

As reported [8], the design of semiconductor quantum dots can be employed for generation of polarization-entangled photon pairs. Here we suggest the quantum dot arrangement described, when placed in nano antenna to be used as a source of deterministic entangled photon source with heralded photon together combined, to achieve high collection efficiency.



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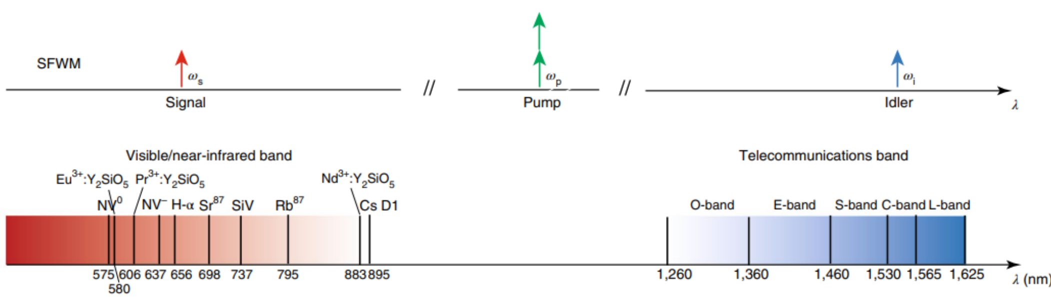
## Coupling efficiency of photon with medium of transmission.

There is a constraint on the development of quantum communication source - a viable or feasible quantum communication it must utilize existing optical infrastructure with minimal change. This requires a source of entangled photons whose bandwidth is compatible with the classical optical fiber network to provide low attenuation and larger distance.

To satisfy this entangled photon bandwidth must be in the telecom band. Entangled photon pairs are generated in non-linear crystals by SPDC [9] and in an optical fiber by the process of SFWM [10-12]. In the SPDC process, single photon generates two entangled photons but phase matching (required for conservation of energy and momentum) lack in this process as natural birefringence is absent in non-linear crystal. In SFWM process provide advantage, here two photons generate two-photon pairs simultaneously which are entangled, one in lower frequency and the other in higher frequency, termed with idler and signal photon respectively. The generated entangled photon phase is in sync with each other and with the parent photons, ultimately satisfying the energy conservation condition [3] given by relation Ws + Wi= 2Wp where Ws, Wi, Wp are frequencies of the signal, idler and pump photons respectively and momentum conservation in a waveguide which involve phase-matching condition.




Lu, X., Li, Q., Westly, D.A. *et al.* Chip-integrated visible–telecom entangled photon pair source for quantum communication. *Nat. Phys.* **15**, 373–381 (2019). https://doi.org/10.1038/s41567-018-0394-3

A device [3] that is the source of entangled photons in the visible-telecom band includes a photon generator coupled with a micro resonator. Through this coupling [3][6], generated photon called pump photon is supplied to a micro ring resonator which generates entangled photon pairs by SFWM [5] process as described above and thus complete setup acts as an entangled photon pair source of visible-telecom band.

Micro-ring resonator based on silicon nanophononics poses limitation of narrowband operation [6]. So, silicon-nitride-based micro-ring resonator provide broad operating wavelength from near-ultraviolet to mid-infrared range, which makes it suitable for use to generate visible-telecom band pairs [3].

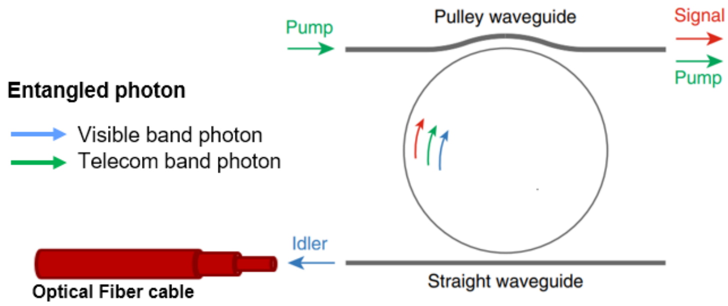



Fig. a, inspired from [3]

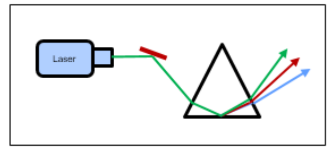
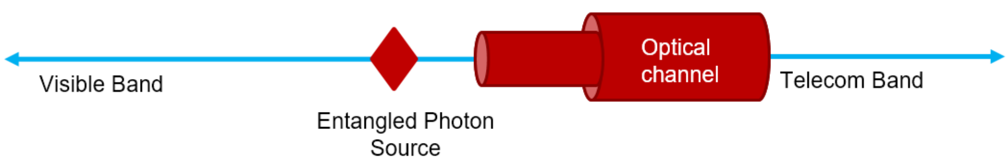



Fig. b, inspired from [5]

In this design [3], Silicon nitride micro ring resonator has silicon dioxide cladding below and a top air cladding to separate generated photon pairs into different output waveguides. The micro ring dispersion depends on the film thickness, ring width, and ring radius, which are taken care of during the design to minimize any dispersion.

The wide frequency separation in photon pair from SFWM process poses a coupling challenge in the resonator to the waveguide as it involves the coupling of visible, telecom, and pumps mode, so two waveguides are employed at top and bottom [3]. The top waveguide, the pulley is designed to wrap around the micro-ring providing extra length interaction for pump and visible mode efficient interaction. Asymmetric cladding and 560nm wide waveguide support single-mode operation allowing visible and pumps photon mode interaction while acting as the cutoff for telecom mode [3]. Similarly in a bottom straight waveguide with width of 1120nm couple’s telecom band operating only in telecom mode.
Design [3] of the micro-ring resonator employs the mode splitting technique by having sinusoidal modulation in the inner surface of the ring. Two optical modes [3] are generated when modulation index matches with the azimuthal order of optical mode i.e., n=2m then degenerate phases are removed and given two modes with one mode located outside of modulation having a higher frequency and the other located inside of modulation having a lower frequency. This frequency splitting is proportional to modulation amplitude [3] and obtained optical mode numbers can be identified by changing modulation period [3].

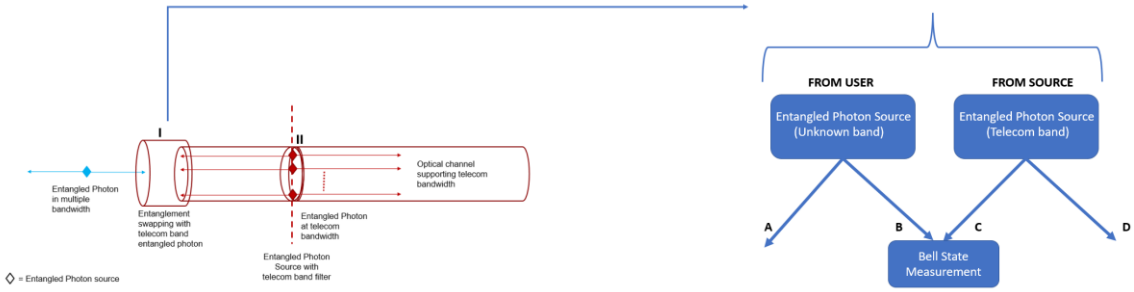



Here we suggest the above discussed methods to be employed at source end (USER) to generate visible and telecom band pair with telecom band interfaced directly to optical fiber for long distance communication at the same time visible photon to be used for interfacing the user information and visible band photon would be used for short distance communication localized to quantum systems.

## Using multiple entangled photon pairs with filters for telecom band and utilizing entanglement swapping

There are various source generation approaches discussed [1] such as hot vapor, cold atoms, semiconductors, quantum dots, nitrogen-vacancy centers in diamond, SPDC. Entangled photons generated in broad spectral range and need spectral filtering like optical cavities or very narrow bandpass filters, that provides the telecom band entangled photon but at the cost of lowering the intensity.

Here, we propose a mechanism to utilize a source that can generate entangled photons in telecom band even at low efficiency or having low intensity of the entangled photon generation rate.




In this setup, an entangled photon source (shown with red box) at position **II**, is placed in the channel, optical fiber. This mechanism employs multiple such sources where the number of sources must be selected precisely matched such that it satisfies our overall entangled photon requirement with an aim to establish continuous entangled photons at telecom band for interaction with user-generated photons at all points in time.

At position **I**, with entanglement swapping [7] that is performing bell state measurement on the photon pairs, one of which belongs to the user entangled photon B with C from source that is at telecom band, resulting in the entanglement of A and D finally transfer the information from the user to traveling photon D in optical cable (telecom band). The same working is applicable for other photon source arrangements in mid optical fiber and its interaction with user photon.

In this mechanism, a user is not responsible to generate photon pairs at the telecom band. A service provider holds the responsibility of coupling the user entangled photon and traveling band entangled photon using entanglement swapping as described.

## Conclusion

After performing literature review on sources, we conclude that different advancements in deterministic generation, increasing collection efficiency, and efficient coupling, when combined and appropriately placed in communication network would help to increase the overall operating efficiency of communication network and help to realize an efficient and feasible way to use existing optical fiber infrastructure for long-distance communication. We proposed to use a source capable of producing entangled photons and a single-photon source with a suitable arrangement to produce entangled photons in a telecom band to support communication.

The Deterministic generation of entangled photon pair by Two-photon emission does not affect the efficiency of entangled photon and makes the source reliable. The use of nano-antenna increases the collection efficiency by providing a high rate of entangled photons. This helps to increase the speed of quantum communication and make the source viable for real-world/practical communication through optical or free-space channels. Finally high compatible source with optical communication help to achieve efficient coupling with the telecom band, so to utilize existing optical fiber infrastructure.

## Data

This paper does not provide any new experimental data but performs literature research and presents a review on achieving efficient sources.

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