An approach to reliable photon sources for Quantum Communication

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***Abstract*—In pursuit of secure communication and with the advent of quantum mechanics, has paved the way to harness the quantum properties of photons for information/data exchange. In realization of a large-scale quantum communication network, requires a reliable single and entangled photon source that can be easily coupled with existing optical and free-space communication infrastructure with minimal change. Quantum dot-based single-photon sources seem to be promising, with the suitably engineered design of its isotropic spatial distribution of generated photon. Nano-antenna embedded quantum dot results in high directional single photon at the numerical aperture of the existing optical fiber with a collection efficiency of greater than 80%. Entangled photon source, a key component of quantum key distribution based on micro-ring resonator with spontaneous four-wave mixing. Its ability to generate entangled photon pairs in desired band wavelengths ensures its feasibility to directly couple with optical fiber. Further, the self-pumping mechanism of an optical amplifier with a resonator eliminated the need for an external laser source. Both the source's ability to work at normal temperature and chip integrated design make it an ideal, reliable source for practical quantum communication over a long distance. We also suggest a scheme to utilize low-intensity telecom band photon sources, arrangements in multiple numbers fulfill the requirement of an entangled photon. This scheme uses entanglement swapping of two sources to transmit information among users. Utilizing available low-intensity entangled photon sources paves the way to the high-speed realization of quantum communication.**

***Index Terms*—Quantum Communication, Quantum mechanics, Quantum dot, Single photon, Entangled photon, Nano-antenna, Optical fiber, Telecom band, Micro-ring resonator, Optical amplifier, Chip integration, Entanglement swapping**

I. Introduction

Confidentiality often finds its way in the exchange of information. Often a conventional way of information transfer faces challenges to the security and confidentiality of information. As in classical communication in its basic form, data is encoded by turning the light source ON and OFF and security to the data is provided by encoding and encryption. The advent of quantum computing and its algorithm pose a direct threat to the encryption of classical communication that paved the way to look for communication to ensure the secure encoding and transfer of information. The exploration of quantum physics is revealing its potential to fulfill this requirement through its principles of superposition, teleportation, no-cloning in quantum information processing. The source forms the key component of communication, where the promise of secured communication resides and to generate photon sources (single/Entangled) for quantum communication. Most of the single-photon sources for quantum communication are random photon generation, operate at very low temperature even at cryogenic temp, have broad spectral bandwidth with the spatial distribution of generated photon that leads to low collection efficiency and low rate of communication. The development of a viable or feasible quantum communication based on entangled pair source must utilize existing optical infrastructure at telecom band and having entangled pair only at telecom band makes it difficult for linking with local quantum systems operating at the visible band. And with entangled pair at visible band used for transmission of quantum information in optical fiber losses are quite high makes it inefficient for long-distance communication. Further, the entangled pair generation is required to be an on-chip integrated photonic setup for its scalability and easy integration to classical channels with minimal change. The integrated on-chip entangled pair sources need to be fed with separate laser sources that make on-chip fabrication quite difficult moreover these lasers used are large require lots of input power and are costly. Need for tunable lasers as a pump source as resonant sources requires the pump to be actively controlled when used as input for high-quality resonators and high pumping powers, as resonant frequencies are sensitive to power and thermal fluctuations.

When addressing the design of a high-speed network, it narrows down to having a photon pairs source that produces a single photon and entangled source at a fast rate, with the source compatible with the channel causing a minimal change in existing infrastructure.

II. Single photon sources

Single-photon as data carrier of quantum communication encodes information in its quantum properties mainly polarization. Most Single-photon sources, so far developed and in use as a limitation that works at very low temperature, i.e. cryogenic temperature, where some have emission is spatially distributed in broad spectral bandwidth. Even though single-photon laser sources work at room temperature but its second-order correlation value equals unity, i.e. emission is random, probabilistic, and fluctuating, that needs filtered set-up. The achievement of a reliable single-photon source needs to be deterministic, consistent, stable, on-demand, anti-bunched essentially at visible/telecom band. From a technology viewpoint, the source needs to be scalable that works at room temperature and coupled to an existing optical fiber infrastructure with minimum change. Here, we suggest Quantum dot(QD)-based, a single-photon source that works at room temperature, with on-demand and deterministic emission that is scalable, with on-network integration instead of a laser and other sources. But Quantum dot needs to be first engineered to avoid its isotropic, broadband emission with low single-photon purity that leads to low coupling efficiency causes the low rate of communication.

In this paper we referenced the work of Hamza et al. [1] that clearly illustrates the use of nano-antenna with quantum dot to achieve highly directional single-photon instead of spatially generated and distributed photons.

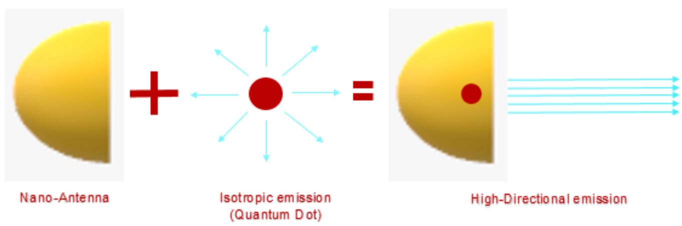

Fig. 1. Quantum dot with antenna design.

A. Fabrication of Nano-antenna

In the preparation, template stripping fabrication creates ultra-smooth nano-antenna. At first Silicon template is fabricated, on which gold metal is deposited and stripped out from the silicon template for the final nano-antenna structure.

B. Integrating Quantum dots on Nano-antenna

On obtained nano-antenna structure, a poly-methyl methacrylate dielectric layer is spin-coated on a nano-antenna surface with a height determined from the distance of QD from metal that reduces metal-induced losses. Further, the gas-phase deposition technique is used to deposit a thin layer of aluminum oxide, AlOx, that ensures the stability of the QD and prevents its sinking into the dielectric medium. This forms the stage for placing a quantum dot on a nano-antenna.

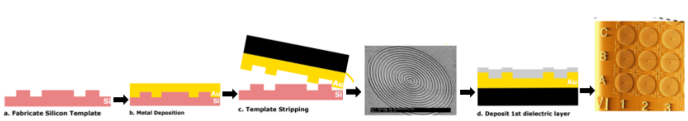

Fig. 2. Nano-antenna fabrication process. [1]

An integrated dual scanning probe microscope along with an optical microscope is used in the QD writing process, where a high-resolution nano-scale topographical map antenna is created using atomic force microscopy (AFM) probe, that is wetted with ink, a colloidal solution of QD – CdSe/CdS with dichlorobenzene (a high boiling liquid) that remains liquid at room temperature. Nano-pipette/AFM probe delivers that QDs droplet at a predetermined location on the substrate. The microscope is used to determine the success and failure of the writing process. On successful placement of QD, the second layer of dielectric is coated on the top to mark the end of QD fabrication in the nano-antenna process.

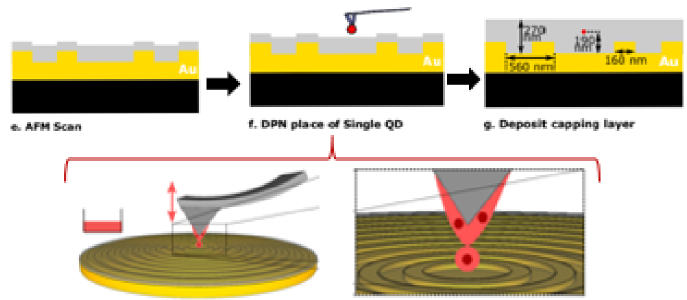

Fig. 3. Quantum dot deposition on nano-antenna. [1]

The number of QD transferred to the antenna is controlled by tip bleeding (release of excess ink from AFM tip), short contact time, and low concentration of QD in ink. This way of high precision placement of QD at the center of nano-antenna increases the collection efficiency, which is seen to degrade when away from the antenna center.

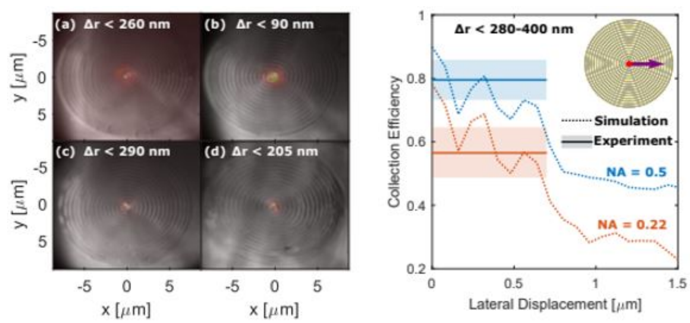

Fig. 4. Luminance of quantum dot (left) and plot of collection efficiency (right) shows the effected of quantum dot placement accuracy at the center of nano-antenna. [1]

C. Outcomes of Quantum dots in nano-antenna

High collection efficiency, greater than 80% with high directionality, high single-photon purity, and brightness level of 0.76 single photons/pulse is obtained using nano-antenna with QD compared to free space. Further, the device achieves good reproducibility, scalability with integrated design. High collection efficiency is obtained in the range of commercially available fibers numerical aperture of 0.22 and 0.5, ensuring its compatibility to directly couple with existing optical fiber infrastructure. With Aluminium Oxide deposit, provides a strong base to QDs with no lifetime reduction at Photon rate of $380KHz$ and pump rate of $500KHz$ that reaches up to $11.5MHz$, for NA of 0.9.

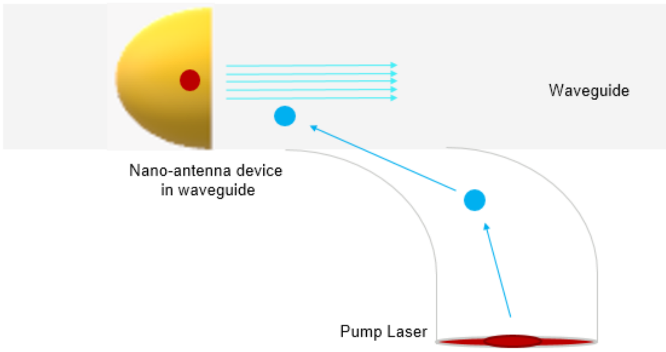

Fig. 5. Nano-antenna quantum dot design with pump excitation

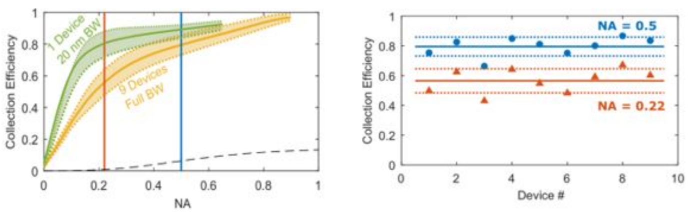

Fig. 6. Collection efficiency of quantum dot in free-space and with nano-antenna (left). Collection efficiency of quantum dot with nano-antenna at available optical fiber numerical aperture (right). [1]

III. Entangled Photon Source

A. *Efficient generation of on-chip integrated entangled photon pair, for an optical medium of transmission*

The development of on-chip entangled photon pairs is a building block in the development of efficient, reliable, and cost-effective sources to realize a large number of photonics-based quantum technologies, such as quantum key distribution (QKD), quantum repeaters, quantum memories, and quantum optical computing. Here suggested setup, [2] silicon nitride microring resonator as the source of entangled photons provide broad operating wavelength from near-ultraviolet to mid-infrared range especially in the visible-telecom band, telecom-telecom band, and visible-visible band. This micro-ring resonator supports a high-quality factor in order of 10^5, which ensures a lower rate of energy loss resulting long photon lifetime in the resonator leading to an increase in the intensity of resonant pump photon and hence reducing the power required to achieve a pair generation rate.

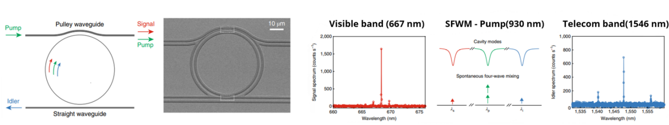

Fig. 7. (Left)Entangled signal and Idler photon band along with Pump photon. (Right)Working and coupling design of on-chip micro-ring resonator. [2]

This design referenced [2] of Silicon nitride microring resonator employs lower silicon dioxide cladding 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, and is kept at a thickness of $500nm$, width of $1,140nm$ and radius of 25μm, to achieve wavelength resonance of $668.4nm$, $934.0nm$ and $1,550.0nm$, respectively for signal, pump and idler photon. The wide frequency separation in photon pair from spontaneous four-wave mixing(SFWM) process poses a coupling challenge in the resonator to the waveguides as it involves the coupling of visible, telecom, and pumps mode, that utilizes two waveguides one at top and other at the bottom. The top waveguide of width $560nm$, the pulley waveguide is wrapped around the micro-ring provides extra interaction length for pump and visible mode. With a coupling length of 33μm and a gap between ring and waveguide around $200nm$ to $250nm$, this asymmetric cladding configured waveguide support a single-mode operation for visible and pump photon acting as the cutoff for telecom mode.

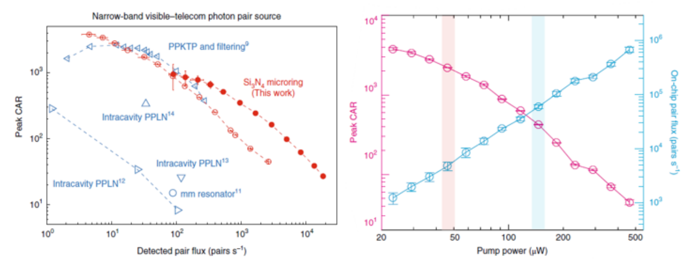

Fig. 8. (Left) Pump-power dependence of the visible–telecom photon pair source CAR and on-chip photon pair flux. (Right) Peak CAR values and the raw detected photon pair flux for narrow-band visible–telecom photon pair sources. [2]

1) *Performance achieved with integrated micro-ring resonator set-up:* At pump power, from a laser source, of around 46μW, the coincidence to accidental ratio(CAR) value is around 2200 ± 14 with photon pair flux of 4800 ± 900 pairs, with the highest CAR measured in this setup is 3780 ± 140 at pair flux of 1200 ± 300 pairs. The waveguide-resonator coupled in the high-quality resonator in the telecom band improves source performance to achieve a pair flux up to 18400 $\pm$ 1000 pairs, maintaining high CARs above 27 making it suitable for practical applications. At an increased pump power of 146μW, CAR is 423 ± 4 with on-chip photon flux 62000 $\pm$ 5000 pairs. This integrated setup collectively provides in results, a narrow-band photon pair with unprecedented purity and brightness, with a CAR up to 3780 ± 140 and a detected photon pair flux up to 18400 ± 1000 pairs. Concerning the visibility of entanglement generated from this setup is observed to be $82.7 \pm 0.2\%$ for $20m$ fiber length, $68 \pm 2\%$ for fiber length of $2.5km$ and $58 \pm 1\%$ for $20.65km$ length in fiber. This on-chip-integrated visible–telecom photon-pair source emitting bright, pure, and narrow-linewidth photons have the potential to serve as an important resource in connecting quantum memories with telecommunication networks to demonstrate visible-telecom entanglement over $20km$ fiber. The visible band photon from entangled pair is used for connecting local quantum systems such as quantum memories and majorly

by the user to encoding information whereas the telecom band photon entangled to visible is directly interfaced to optical fiber for long-distance communications. Moreover, the advantage of on-chip integrated entangled photon sources for QKD is its compatibility with classical photonics technology and is well suited with existing infrastructure and industry for its low-cost, high performance, and scalability.

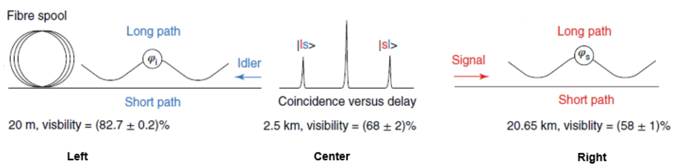

Fig. 9. Distribution of entanglement over the distance on the optical fiber for visible and telecom band. [2]

B. *Self-pumping setup for on-chip integrated entangled photon pair generation*

To achieve micro ring resonances without a dedicated external laser as in the work of Peccianti et al. [3], we advocate utilizing the output pump photon that gets filtered out (using edge pass filters from the output of micro-ring resonator). This pump photon is collected at the pulley waveguide, to be used in the self-pumping configuration. The pumping scheme attached to the micro ring resonators employs an optical amplifier, moreover semiconductor amplifier for the electrical pumping of the system. In this paper, we reference the work of Francesco et al. [4] of generating entangled photon in fiber loop cavity containing microring resonator in a self-pumped configuration. Here, we suggest utilizing this scheme in the silicon nitride microring resonator as previously mentioned, for the generation of visible and telecom band entangled pairs.

As inspired from the work of Francesco et al. [4], the on-chip integrated silicon Nitride microring resonator is inserted in the external fiber loop cavity containing optical amplifier, to which light is coupled in and out using polarized fibers forming a closed cavity. Two bandpass filters in the cavity, one at the input and the other at the output of the amplifier keep the resonances of the pump centered around the cavity. Amplified spontaneous emission from an optical amplifier is suppressed by a bandpass filter (BPF) at the output of the optical amplifier whereas amplification of spontaneous emission in micro-ring is rejected BPF, at the input of an optical amplifier. In this setup, a $99 : 1$ fiber beam splitter is used to measure the power of the traveling radiation in the cavity along with a fibered Fabry-Perot etalon in the cavity ensures continuous lasing action on a single longitudinal mode.

In this self-pump configuration, the part shown in the red box, the optical amplifier provides the optical feedback required for lasing action and micro-ring resonances modulates the round trip losses of a cavity, hence automatically causing resonances at one of the ring's resonance frequencies required to produce signal and idle pair by SFWM.

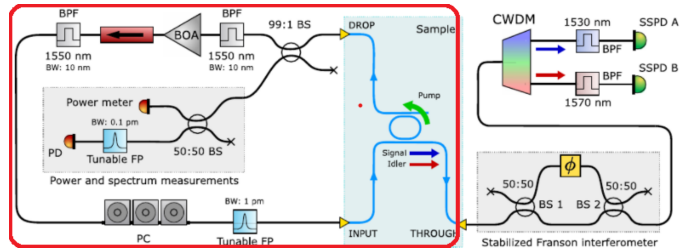

Fig. 10. Experimental Setup (RED Box) [4] : BOA, booster optical amplifier; BPF, band pass filter; FP, Fabry–Perot; PC, polarization controller

In the circulation of a photon in the cavity, photon experiences losses due to out-coupling with wave-guide, grating couplers, and BPFs of around 10.5 dB which is supplied from an optical amplifier. The pump photon from the output of the micro-ring resonator experiences a drop in power compared to the input to micro-ring, which is measured using a power meter with help of $99 : 1$ beam splitter. For this loss, an optical amplifier provides gain for the radiation of one of the ring resonances to obtain lasing and is fed back to the micro-ring resonator loop that lifts the need of having an external bulky and costly laser source in the cavity. QKD based on entangled photon sources using Silicon Nitride micro-ring resonators using the process of SFWM is the important candidate for encoding information in quantum optics and quantum communications. This setup promises the advantage of compatibility with classical photonics technology and is well suited with existing infrastructure and industry for its low-cost, high performance, and scalability. It is a step forward in the realization of Integrating all the building blocks necessary to produce high-quality photonic entanglement in the visible–telecom wavelength range out on a single integrated photonic on-chip.

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

The sources generating entangled photons in broad spectral range need spectral filtering such as optical cavities or very narrow bandpass filters to provide telecom band entangled pairs at cost of low intensity.

In this paper, we introduce a mechanism to utilize an entangled pair source with filters generated in telecom band even at low intensity or generation rate.

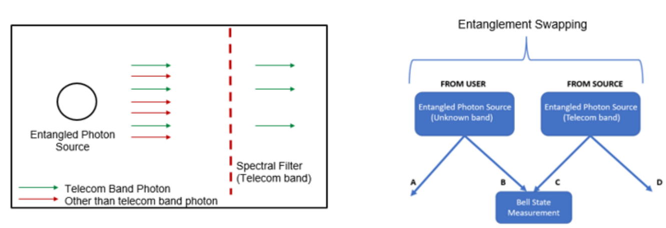

Fig. 11. (Left)Entangled photon source with spectral filter. (Right)Entanglement swapping between a photon from user pair and a photon of travelling pair

This scheme fig.12, consists of two-photon source arrangements. One composed of multiple entangled pair sources with filters at a position I, with the number of sources selected precisely, to ensure a photon from entangled pair available at position II, all time. Another is an entangled photon pair source that resides with the user for quantum information encoding.

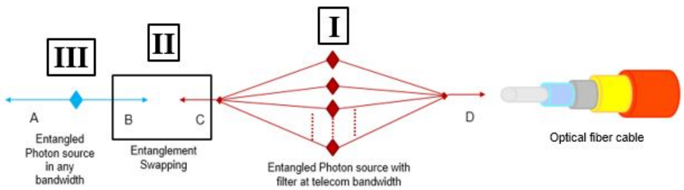

Fig. 12. Scheme for utilising low intensity entangled photon source along with user entangled photon.

From entangled photon pair at telecom band at a position I, say C and D, photon D is directly coupled to optical fiber whereas another photon C, is made available to position II in order to link with distant quantum systems. From the user entangled pair, say A and B, at position III, photon B is available at position II that undergoes entanglement swapping with photon C by bell state measurement, which in turn entangles photon A and D.

Photon A from entangled pair is with the user for encoding quantum information, which travels with photon D in optical cable (telecom band). In this scheme, the user is not responsible to generate and encode information in entangled photon pairs at the telecom band, rather a service provider holds the responsibility of coupling the user entangled photons operating at any band with traveling telecom band entangled photon that ensures to achieve reliable transfer in the long-distance communications.

V. Conclusion

In this paper, we came across different advancements to achieve feasible quantum communication either single-photon sources or entangled photon sources. A feasible single-photon source, in quantum communication, is needed to work at room temperature with a correlation factor less than 1 to provide anti-bunching single-photon and engineered in a way to keep a balance between the high collection efficiency and coupling to the optical infrastructure. For entangled photon source efficiently utilizing long-distance communication, needs an integrated on-chip setup to merge especially optical fiber and local quantum systems, operating in visible and telecom band. Moreover, in this paper, we also discussed an approach that acts as an on-chip laser source and eliminates the need for an external tunable laser. This would prove to be a key step in realizing a fully on-chip integrated, stable, scalable, low-cost, long-distance entangled pair sources along with an on-chip laser source that can be coupled to existing optical fiber infrastructure. Our future work will focus on simulation of entangled pair generation from a micro-ring resonator and further combining nano-antenna-based single-photon source with micro-ring resonator to evaluate the overall efficiency of the device along with a detailed study of the fabrication process involved in different stages.

VI. Data

This paper does not provide new experimental data, it is based on literature research to suggest an approach to achieving reliable, chip-integrated single and entangled photon sources that can be used with existing optical communication infrastructure with minimal changes.

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