INTRASYSTEM ENTANGLEMENT GENERATOR AND UNAMBIGUOS BELL STATES DISCRIMINATOR ON CHIP

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ABSTRACT

Bell measurements, jointly projecting two qubits onto the so-called Bell basis, constitute a crucial step in many quantum computation and communication protocols, including dense coding, quantum repeaters, and teleportation-based quantum computation. A problem is the impossibility of deterministic unambiguous Bell measurements using passive linear optics, even when arbitrarily many auxiliary photons, photon-number-resolving detectors, and dynamical (conditionally changing) networks are available. Current proposals for going over the 50% upper bound without using experimentally challenging nonlinearities rely on using entangled photon ancilla states and a sufficiently large interferometer to combine the signal and ancilla modes. We demonstrate that the novel Multiple Rail architecture, based on the propagation of a single photon in a complex multipath optical circuit (or multiwaveguide optical circuit), provides the possibility to perform deterministic Bell measurements so to unambiguously discrimate all four Bell States.

Index Terms— Quantum communication, Quantum computing, Entanglement, Quantum gates.

1. INTRODUCTION

Quantum technology is a fundamentally new way of harnessing Nature, it has potential for a truly revolutionary innovation and promise the next generation of products with exciting and astounding properties that will affect our lives profoundly. They will have a great influence in defence, aerospace, energy and telecommunication sectors. If this process is to continue in the future, new, quantum technology will replace or supplement what we have now. In particular, Quantum Information Technology can support entirely new modes of information processing based on so called quantum bits or qubits. Its eventual impact may be as great as or greater than that of its classical predecessor. There is almost daily progress in developing promising technologies for realizing quantum information processing with various advantages over their classical counterparts [1–31].

Photons are unsurpassed as qubits in terms of decoherence times, mobility and achievability of high-fidelity single-qubit operations. Thus far, entanglement experiments in optics have been very clean, and an optical quantum processor would obviously have an advantage in connecting to a quantum "network" (no need to convert between stationary and flying qubits). All-optical quantum processing became feasible when, in 2001, a breakthrough known as the KLM (Knill-Laflamme-Milburn) scheme showed that scalable quantum computing is possible using only single-photon sources and detectors, linear optical circuits and quantum teleportation: recent approaches based on cluster states or error encoding made an all-optical architecture are serious contenders for the ultimate goal of a large-scale quantum computer. This scheme relies on quantum interference with auxiliary photons at a beam splitter and single-photon detection to induce not-deterministic interactions. In the past ten years, the KLM scheme has moved from a mathematical proof of concept, towards practical realization, with demonstrations of simple quantum algorithms and theoretical developments that dramatically reduce the resource overhead [32].

Optical integrated circuits offer great potential for realizing previously unfeasible large-scale quantum circuits. This flexible architecture can be used to implement key quantum-computation elements, including universal $Control - NOT$ ($CNOT$) gates based on integrated directional couplers and reconfigurable single-qubit operations using phase controllers based on the thermo-optical effect of silica. However, this architecture suffers not only of the overhead of multiple sources, detectors and ancillary qubits, but it needs to maintain the complete coherence between single photons in which qubits are encoded [33–41]. Existing schemes typically require thousands of single photon sources (photon guns), temporal (and spectral) coherence between photon sources, extensive adaptive switching which is experimentally challenging, noisy large quantum memories for repeat-until-success strategies. To overcome the KLM limitation, we introduced a novel architecture and physical representation of a quantum machine. The idea is based on the exploitation of the so called "Classical Entanglement". “Classical Entanglement” or “Intra-System Entanglement” should not be confused with “entanglement simulations in classical op-

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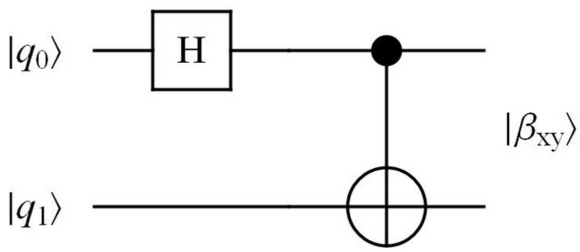

Fig. 1. Scheme of a Bell States generator in terms of quantum gates.

tics", but it denotes the occurrence of some mathematical and physical aspects of quantum entanglement in classical beams of light. We show the possibility to encode the whole state space in a complex optical circuit based on Multiple Rail (MR) architecture: any quantum state is encoded and processed trough different single-mode waveguide [42, 43]. Therefore, it is possible to realize quantum devices that show deterministic and not probabilistic behavior, as quantum entanglers, Bell measurements and teleportation schemes. Bell measurements, jointly projecting two qubits onto the so-called Bell basis, constitute a crucial step in many quantum computation and communication protocols, including dense coding, quantum repeaters, and teleportation-based quantum computation. A Multiple Rail (MR) architecture, based on the propagation of a coherent pulse in a complex multipath optical circuit, provides unambiguous discrimination of all four Bell States and deterministic teleportation.

2. BELL STATE SYNTHESIZER

The deep ways that quantum information differs from classical information involve the properties, implications and uses of quantum entanglement. Entanglement has always been a key issue in the ongoing debate about foundation and interpretation of Quantum Mechanics, since Einstein and Schroedinger expressed their deep disatisfaction about this astoneshing part of quantum theory. Untill 1965, when Bell published the famous inequality by which he demonstrated that EPR's (Einnstein, Podolsky and Rosen) local and realistic vision of world was wrong, all discussions about entanglement were theoretical, sometimes metatheoretical or metaphysical. Nowadays entanglement is a physical resource and a fondamental key for quantum information and in particular for quantum computing, then it is fundamental task the engineering of entanglement syntetizer. The logic operation sequence that provides entanglement syntesis by starting from two independent qubits is obtained by the circuit shown in Fig.(1). The circuit represents the product of $Hadamard$ gate (H) applied to the first qubit followed by $CNOT$, with the first bit as the source and the second bit as the target. It is straightforward to see that this circuit transforms the standard basis to the entangled basis

$$\begin{aligned}
|00\rangle &\Longrightarrow |\beta_{00}\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right) = \left|\Phi^{+}\right\rangle, \\
|01\rangle &\Longrightarrow |\beta_{01}\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle + |10\rangle\right) = \left|\Psi^{+}\right\rangle, \\
|10\rangle &\Longrightarrow |\beta_{10}\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle - |11\rangle\right) = \left|\Phi^{-}\right\rangle, \\
|11\rangle &\Longrightarrow |\beta_{11}\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle - |10\rangle\right) = \left|\Psi^{-}\right\rangle. \qquad (1)
\end{aligned}$$

Similarly, we can invert the transformation by running the circuit backwards (since both $CNOT$ and H square to the identity); if we apply the inverted circuit to an entangled state, and then measure both bits, we can learn the value of both the phase bit and the parity bit. Of course, H acts on only one of the qubits; the "nonlocal" part of our circuit is the $CNOT$ gate – this is the operation that establishes or removes entanglement. We can rewrite the product $CNOT \cdot (H \otimes I)$ in $CNOT \cdot SWAP \cdot (I \otimes H) \cdot SWAP$ so that we can implement the Bell Synthesizer by the physical circuit described in Fig.(2). The Mach-Zehnder (MZ) interferometer is the building block for the engeneering of the quantum gates. Consider two orthogonal optical modes represented by the annihilation operators $\hat{a}$ and $\hat{b}$ and the vacuum modes $|0\rangle_a$ and $|0\rangle_b$. We define our logical qubits as $|\mathbf{0}\rangle = \hat{a}^{\dagger}|00\rangle$ and $|\mathbf{1}\rangle = \hat{b}^{\dagger}|00\rangle$.

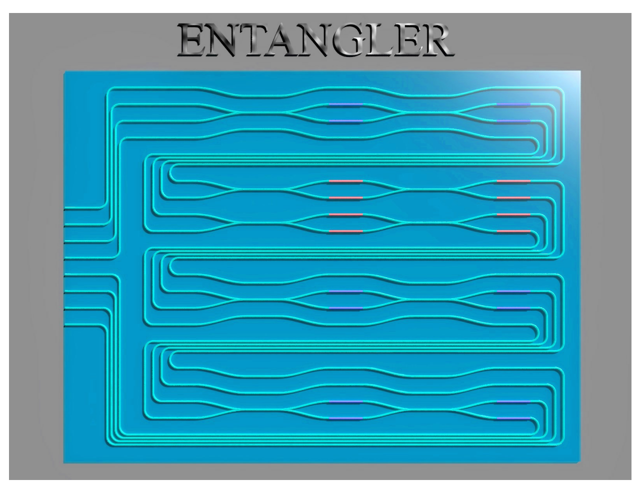

Fig. 2. Physical implementation of a Bell State Synthesizer.

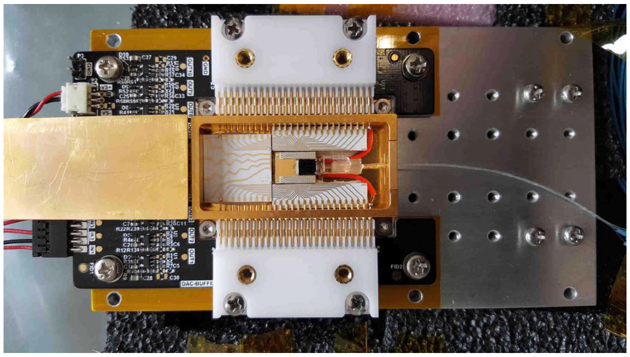

Fig. 3. Optical, Electronics and mechanics integration of InP Entangler. Note the gold contacts for MZ voltage setting and control, and thermistor to thermalize the integrated structure.

That is, single photon occupation of one mode represents a logical zero, whilst single photon occupation of the other represents a logical one. Let us consider a Mach-Zehnder interferometer. The first beam splitter prepares a superposition of possible paths, the phase shifters inside modify quantum phases in different paths and the second beam-splitter combines all the paths together. By setting the first phase-shifter we are able to control the amplitude probability to obtain the single photon in the first or in the second path. A second phase shifter can control the phase factor between the two amplitude probabilities, so that the MZ interferometer is a universal single qubit gate. The extension of the "dual rail" configuration to a "multiple rail" one provides two- qubit gates, as $Hadamard$, $SWAP$ and $CNOT$ gate.

3. PHYSICAL IMPLEMENTATION OF THE BELL STATE SYNTHESIZER

We used the InP technology to engineering the Bell States generator. In Fig.(3) the scheme of the physical chip is showed. In particular, it is possible to appreciate the smart input-output system so that a single bundle of eight fiber provides the injection and the extraction of light pulses. The gold metalized contacts on the top of waveguides provide to set the voltage for the fine control of each Mach Zehnder interferometer. To implement the X Pauli gates we used symmetric MZ (i.e without differential path length between upper and lower arms) which are in cross state by default. To implement $HADAMARD$ gate, in order to change the MZ initial state from cross operation to $50/50$ operation, a differential path length equivalent to a $\pi/2$ phase shift has been introduced. The length increment is $118nm$ assuming an effective refractive index $neff = 3.28@1.55\mu m$ wavelength. This length increment is in the order of the process resolution (about $200nm$) making the initial state uncertain. The InP Chip is integrated in a custom packaging which provides the external electrical connectorization for each quantum gate and thermalization thanks to a thermistor. The electrical control of each Mach Zender is performed by a Custom Polarizing Board. A mechanical structure provides the assembly of all single components. The metallic holed base also gives a strong support to protect the bundle of Polarizing Maintaining fibers. After the packaging and the integration the Mach Zehnders of each quantum gate were characterized in terms of Voltage-Current curve and in terms of optical response.

4. EXPERIMENTAL BELL STATE GENERATION AND UNAMBIGUOS DISCRIMINATION WITHOUT ANCILLA

In the experiment, an attenuated coherent state with an avarage number of photon $\mu = 0.1$ was injected in the first waveguide of the Bell State generator. The first waveguide corresponds to the state $|00\rangle$, so that at the output of the chip we have the excitation of the Bell state $|\Phi^+\rangle$, that is the quantum superposition of the state $|00\rangle$ and $|11\rangle$ with the same probability amplitude. Now we introduce the operation represented in Fig.(4): the Bell state generator creates an entangled state, which is subjected to a total swap gate with a supplementary phase shifting. After the operation a Bell measurement is applied on the new state. In the physical implementation the Polarization Maintaining output fibers are short-cutted and an external phase modulator is inserted to control the relative phase of the states $|00\rangle$ and $|11\rangle$. The phase shifter provides the state $\left(|00\rangle + e^{i\varphi}\,|11\rangle\right)/\sqrt{2}$ that is re-injected in the chip and measured by four single photon detectors (ID Quantique), one detector for each input (output) fiber. In particular, only the first and the third waveguides, corresponding to the states $|00\rangle$ and $|10\rangle$, will be excited, and the following phase dependent response will be obtained:

$$\Phi_{out} = \cos^2\left(\frac{\varphi}{2}\right)|00\rangle + i\sin^2\left(\frac{\varphi}{2}\right)|10\rangle\,.$$

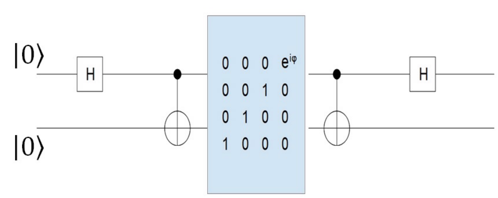

Fig. 4. The Bell state generator create an entangled state, which experiments a total swap gate and a supplemetary phase shifting. Then a Bell measurement provides the discrimination of the new state..

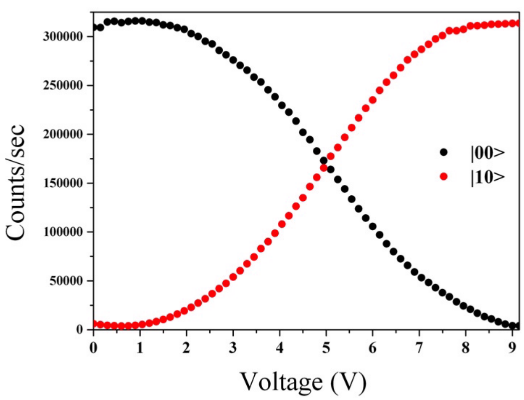

Fig. 5. Discrimination of entangled states by a Bell measurement. By changing the voltage applied to the external phase-shifter the state Φ^+ is transformed in the state Φ^-. The chip provides unambiguos Bell measurements with a visibility better than 99%. The error bar is smaller of the dot dimension.

The experimental results are shown in Fig.(5). The visibility of the curves, defined as $(Max - Min) / (Max + Min)$, is better than 99%, and provides a clear discrimination of the states. The outputs corresponding to the state $|01\rangle$ and $|11\rangle$ are negligeble and not reported in Fig.(5). A Conventional Bell measurement, based on a $50/50$ Beam Splitter and two Polarizing Beam Splitters, can not discrimante between Φ^+ and Φ^- state [20].

5. CONCLUSIONS

We demonstrated the operation of Bell state synthesizer on chip based on InP technology. With the same chip an unambiguos Bell measurement was performed with very high visibility. The high level experiment and the results show that more complex circuits can be built with the same architecture and technology to perform more complicated logic operations. Finally, the introduction of the multiple rail architecture could make a practical quantum computer a reality. The investigation has started from the designing of building blocks, and it follows up with their engeneering and final integration in a first pototype of reconfigurable quantum processor able to perform complex operations.

The architecture is efficient and can be extended to high number of qubits. The important difference with other schemes of quantum computing is that we do not need to repeat the calculation a lot of times with "single photon states", but we just perform the operation in a single shot by using a pulse with a lot of photons. In fact, with this architecture each photon of the pulse will interact only with itself, and it will contribute to the total result of the computation in a single shot. This feature will provide the use of off-the-shelf integrated laser systems and classical detectors (not single photon detectors): then the engineering, and the realization of large circuits able to perform very complex calculations is possible with the current technology. As an example, to complete an elaboration with a "conventional" optical quantum computer we need to repeat calculation for 1 sec with a clock of 1GHz; with this new architecture we can perform one calculation per clock's cycle: we can perform 1 Giga operation per second. An other amazing property of this architecture is the possibility of reconfiguration of the gate: it realizes a sort of quantum FPGA. This demonstrates that, in principle, the same device can solve different kind of computations.

6. REFERENCES

[1] Nielsen, M. A. & Chuang, I. L. Quantum Computation and Quantum Information (Cambridge University Press, 2000).

[2] Knill, E. Quantum computing with realistically noisy devices Nature 434, 39-44 (2005)

[3] DiVincenzo, D. P. The physical implementation of quantum computation. Fortschr. Phys. 48, 771–783 (2000)

[4] Mizel, A., Lidar, D. A. & Mitchell, M. Simple proof of equivalence between adiabatic quantum computation and the circuit model. Phys. Rev. Lett. 99, 070502 (2007)

[5] Raussendorf, R. & Briegel, H. J. A one-way quantum computer. Phys. Rev. Lett. 86, 5188–5191 (2001)

[6] Cory, D. G., Fahmy, A. F. & Havel, T. F. Ensemble quantum computing by NMR-spectroscopy. Proc. Natl Acad. Sci. USA 94, 1634–1639 (1997)

[7] Gershenfeld, N. A. & Chuang, I. L. Bulk spin resonance quantum computation. Science 275, 350–356 (1997)

[8] Ryan, C. A., Moussa, O., Baugh, J. & Laflamme, R. Spin based heat engine: demonstration of multiple rounds of algorithmic cooling. Phys. Rev. Lett. 100, 140501 (2008)

[9] Shor, P. W. & Jordan, S. P. Estimating Jones polynomials is a complete problem for one clean qubit. Quant. Inform. Comput. 8, 681–714 (2008)

[10] Schmidt, H. & Imamoglu, A. Giant Kerr nonlinearities obtained by electromagnetically induced transparency. Opt. Lett. 21, 1936–1938 (1996)

[11] Duan, L. M. & Kimble, H. J. Scalable photonic quantum computation through cavity-assisted interactions. Phys. Rev. Lett. 92, 127902 (2004)

[12] Gruber, A. et al. Scanning confocal optical microscopy and magnetic resonance on single defect centers. Science 276, 2012–2014 (1997)

[13] Devitt, S. J. et al. Photonic module: an on-demand resource for photonic entanglement. Phys. Rev. A 76, 052312 (2007)

[14] Wineland, D. J. et al. Experimental issues in coherent quantum-state manipulation of trapped atomic ions. J. Res. Natl. Inst. Stand. Technol. 103, 259–328 (1998)

[15] Wineland, D. & Blatt, R. Entangled states of trapped atomic ions. Nature 453, 1008–1014 (2008)

[16] Ospelkaus, C. et al. Trapped-ion quantum logic gates based on oscillating magnetic fields. Phys. Rev. Lett. 101, 090502 (2008)

[17] Garcia-Ripoll, J. J., Zoller, P. & Cirac, J. I. Speed optimized two-qubit gates with laser coherent control techniques for ion trap quantum computing. Phys. Rev. Lett. 91, 157901 (2003)

[18] Leibfried, D., Blatt, R., Monroe, C. & Wineland, D. Quantum dynamics of single trapped ions. Rev. Mod. Phys. 75, 281–324 (2003)

[19] Home, J. P. et al. Complete methods set for scalable ion trap quantum information processing. Science 325, 1227–1230 (2009)

[20] Dik Bouwmeester et al,"Experimental quantum teleportation", Nature volume 390, pages 575–579 (11 December 1997)

[21] Dür, W., Briegel, H. J., Cirac, J. I. & Zoller, P. Quantum repeaters based on entanglement purification. Phys. Rev. A 59, 169–181 (1999)

[22] Duan, L.-M. & Raussendorf, R. Efficient quantum computation with probabilistic quantum gates. Phys. Rev. Lett. 95, 080503 (2005)

[23] Morsch, O. & Oberthaler, M. Dynamics of Bose-Einstein condensates in optical lattices. Rev. Mod. Phys. 78, 179–215 (2006)

[24] Vandersypen, L. M. K. et al. Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance. Nature 414, 883–887 (2001)

[25] Kane, B. E. A silicon-based nuclear spin quantum computer. Nature 393, 133–137 (1998)

[26] Neumann, P. et al. Multipartite entanglement among single spins in diamond. Science 320, 1326–1329 (2008)

[27] Wu, E. et al. Room temperature triggered single-photon source in the near infrared. New J. Phys. 9, 434 (2007)

[28] Sanaka, K., Pawlis, A., Ladd, T. D., Lischka, K. & Yamamoto, Y. Indistinguishable photons from independent semiconductor nanostructures. Phys. Rev. Lett. 103, 053601 (2009)

[29] Vion, D. et al. Manipulating the quantum state of an electrical circuit. Science 296, 886–889 (2002)

[30] Harris, R. et al. Experimental demonstration of a robust and scalable flux qubit. Preprint at http://arxiv.org/abs/0909.4321 (2009)

[31] Tian, L., Rabl, P., Blatt, R. & Zoller, P. Interfacing quantum-optical and solid-state qubits. Phys. Rev. Lett. 92, 247902 (2004)

[32] Knill, E., Laflamme, R. & Milburn, G. J. A scheme for efficient quantum computation with linear optics. Nature 409, 46–52 (2001)

[33] Fushman, I. et al. Controlled phase shifts with a single quantum dot. Science 320, 769–772 (2008)

[34] Politi, A., Matthews, J. C. F. & O'Brien, J. L. Shor's quantum factoring algorithm on a photonic chip. Science 325, 1221 (2009)

[35] O'Brien, J. L. Optical quantum computing. Science 318, 1567–1570 (2007)

[36] Migdal, A. & Dowling, J. eds. Single-photon detectors, applications, and measurement. J. Mod. Opt. 51, (2004)

[37] Hadfield, R. H. Single-photon detectors for optical quantum information applications. Nature Photon. 3, 696–705 (2009)

[38] Grangier, P., Sanders, B. & Vuckovic, J. eds. Focus on single photons on demand. New J. Phys. 6, (2004)

[39] Shields, A. J. Semiconductor quantum light sources. Nature Photon. 1, 215–223 (2007)

[40] Matthews, J. C. F., Politi, A., Stefanov, A. & O'Brien, J. L. Manipulation of multiphoton entanglement in waveguide quantum circuits. Nature Photon. 3, 346–350 (2009)

[41] Chang, D. E., Sørensen, A. S., Hemmer, P. R. & Lukin, M. D. Quantum optics with surface plasmons. Phys. Rev. Lett. 97, 053002 (2006)

[42] Falk Töppel, Andrea Aiello, Christoph Marquardt, Elisabeth Giacobino and Gerd Leuchs. Classical entanglement in polarization metrology. New Journal of Physics 16 (2014) 073019

[43] F. A. Bovino, "Efficient Photonic Quantum Computing," in 2015 European Conference on Lasers and Electro-Optics - European Quantum Electronics Conference, (Optical Society of America, 2015), paper CD_9_3.