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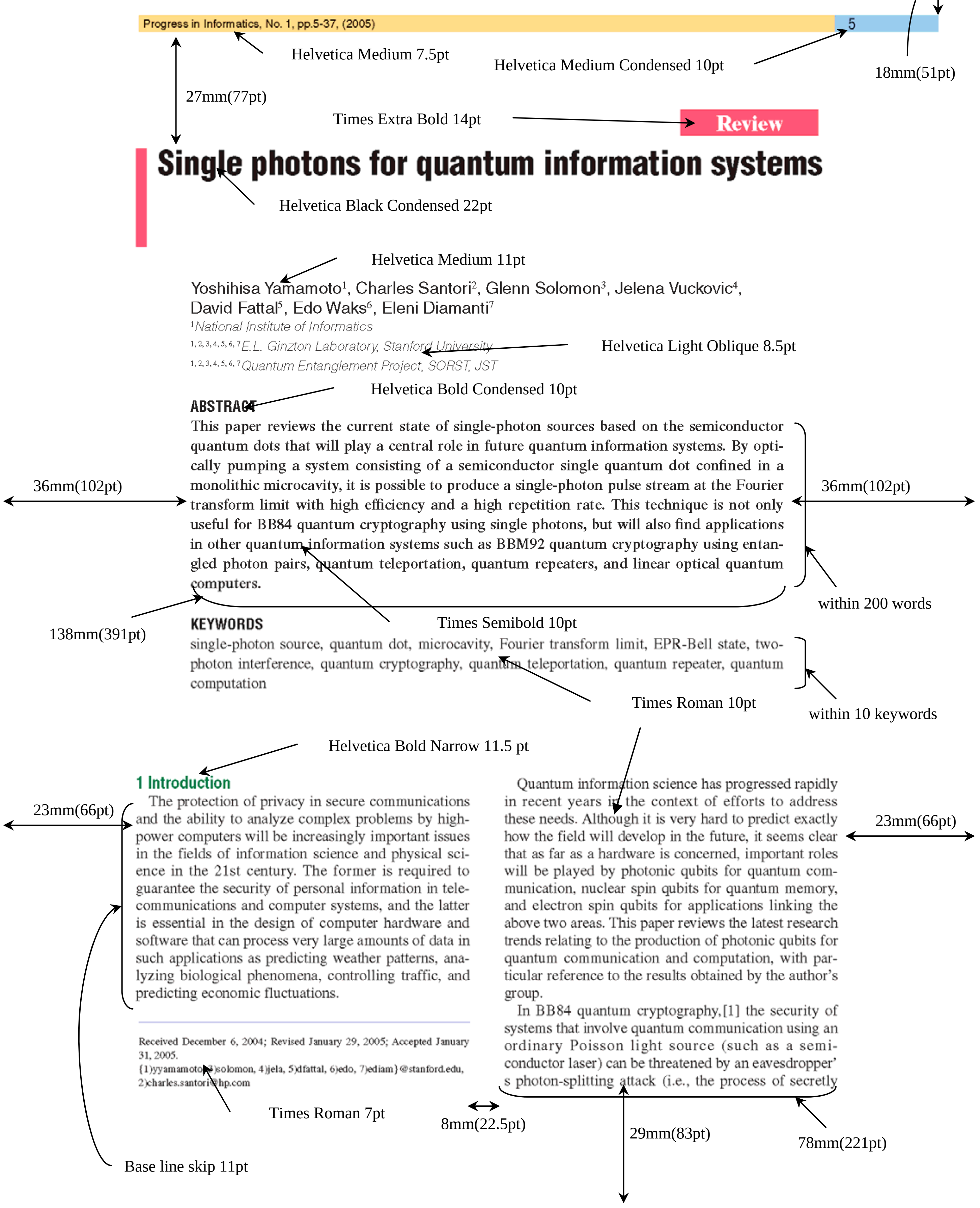

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Review

Single photons for quantum information systems

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ABSTRACT

This paper reviews the current state of single-photon sources based on the semiconductor quantum dots that will play a central role in future quantum information systems. By optically pumping a system consisting of a semiconductor single quantum dot confined in a monolithic microcavity, it is possible to produce a single-photon pulse stream at the Fourier transform limit with high efficiency and a high repetition rate. This technique is not only useful for BB84 quantum cryptography using single photons, but will also find applications in other quantum information systems such as BBM92 quantum cryptography using entangled photon pairs, quantum teleportation, quantum repeaters, and linear optical quantum computers.

KEYWORDS

single-photon source, quantum dot, microcavity, Fourier transform limit, EPR-Bell state, two-photon interference, quantum cryptography, quantum teleportation, quantum repeater, quantum computation

1 Introduction

The protection of privacy in secure communications and the ability to analyze complex problems by high-power computers will be increasingly important issues in the fields of information science and physical science in the 21st century. The former is required to guarantee the security of personal information in telecommunications and computer systems, and the latter is essential in the design of computer hardware and software that can process very large amounts of data in such applications as predicting weather patterns, analyzing biological phenomena, controlling traffic, and predicting economic fluctuations.

Quantum information science has progressed rapidly in recent years in the context of efforts to address these needs. Although it is very hard to predict exactly how the field will develop in the future, it seems clear that as far as a hardware is concerned, important roles will be played by photonic qubits for quantum communication, nuclear spin qubits for quantum memory, and electron spin qubits for applications linking the above two areas. This paper reviews the latest research trends relating to the production of photonic qubits for quantum communication and computation, with particular reference to the results obtained by the author's group.

In BB84 quantum cryptography,[1] the security of systems that involve quantum communication using an ordinary Poisson light source (such as a semiconductor laser) can be threatened by an eavesdropper's photon-splitting attack (i.e., the process of secretly

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probability arbitrarily close to one[7],[50].

We use quantum mechanically indistinguishable photons from a quantum-dot single-photon source, featuring high suppression of two-photon pulses. The fidelity of the teleportation depends critically on the quantum indistinguishability of two photons emitted independently by the single-photon source. A similar experiment was performed in the past using two photons emitted spontaneously by parametric down conversion (PDC)[51]. However, the efficiency of such a process is intrinsically limited by the presence of two-photon pulses, which makes it unsuitable when more identical photons are needed, e.g. to implement the improved teleportation scheme. To date, demonstration of single-mode teleportation with a single-photon source remains a capital step in efforts toward scalable LOQC.

Single-mode teleportation in its simplest form involves two qubits, a target and an ancilla, each defined by a single photon occupying two optical modes (see Fig. 16).

The target qubit can a priori be in an arbitrary state $\alpha|0\rangle_L + \beta|1\rangle_L$ where the logical $|0\rangle_L$ and $|1\rangle_L$ states correspond to the physical states $|1\rangle_1|0\rangle_2$ and $|0\rangle_1|1\rangle_2$ respectively, in a dual rail representation. The ancilla qubit is prepared with a beam-splitter (BS a) in the coherent superposition $\frac{1}{\sqrt{2}}\left(|0\rangle_L + |1\rangle_L \right. = \frac{1}{\sqrt{2}}\left(|1\rangle_3|0\rangle_4 + |0\rangle_3|1\rangle_4\right)$. One rail of the target (mode 2) is mixed with one rail of the ancilla (mode 3) with a beam-splitter (BS 1), for subsequent detection in photon counters C and D. For a given realization of the procedure, if only one photon is detected at detector C, and none at detector D, then we can infer the resulting state for the output qubit composed of mode (1) and (4):

$$\psi_C = \alpha|0\rangle_L + \beta|1\rangle_L = \alpha|1\rangle_1|0\rangle_4 + \beta|0\rangle_1|1\rangle_4$$

which is the initial target qubit state. Similarly, if D clicks and C does not, then the output state is inferred to be:

$$\psi_D = \alpha|0\rangle_L - \beta|1\rangle_L = \alpha|1\rangle_1|0\rangle_4 - \beta|0\rangle_1|1\rangle_4$$

which again is the target state -- except for an additional phase shift of π, which can be actively corrected. Half of the time, either zero or two photons are present at counters C or D, and the teleportation procedure fails. It is interesting and somewhat enlightening to describe the same procedure in the framework of *single rail logic*. In this framework, each optical mode supports a whole qubit, encoded in the presence or absence of a photon, and single-mode teleportation can be viewed as entanglement swapping. Indeed, for the particular values $\alpha=\beta=\frac{1}{\sqrt{2}}$ modes 1 and 2 find themselves initially in the Bell state $|\psi^+\rangle_{12}$, while modes 3 and 4 are in a similar state $|\psi^+\rangle_{34}$. Partial Bell measurement takes place using BS 1 and counters C/D, which (if it succeeds) leaves the system in the entangled state $|\psi^+\rangle_{14}$, so that entanglement swapping occurs. In the rest of this paper, we will consider the scheme in the dual rail picture, since it is a more robust, and hence realistic, way of storing quantum information (at the expense of using two modes per qubit).

The success of teleportation depends mainly on the transfer of coherence between the two modes of the target qubit. If the target qubit is initially in state $|0\rangle_L =$

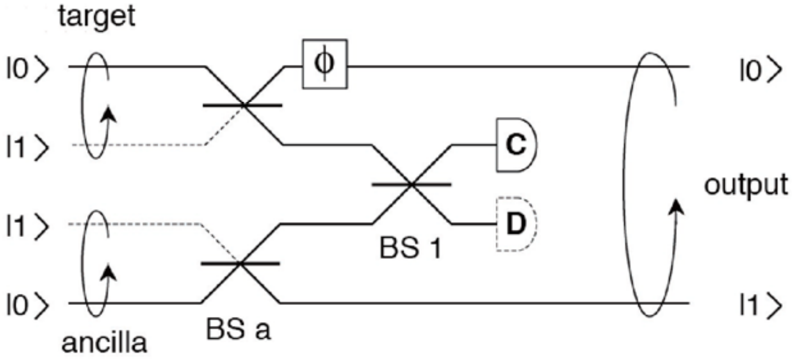

Fig. 16 Schematic of single-mode teleportation. Target and ancilla qubits are each defined by a single photon occupying two optical modes. When detector C clicks and D does not, the state of the remaining modes reproduces the state of the target. The coherence between modes (1) and (2) of the target was transferred to coherence between the same mode (1) of the target and mode (4) of the ancilla. Preparing the target in an equal superposition state makes it easier to measure the transfer of coherence.

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