



Design and implementation of polarization filter for quantum states discriminator in optical quantum communication

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ARTICLE INFO

Article history:

Received 28 July 2009

Accepted 27 December 2009

Keywords:

Quantum state discriminator

Polarization filter

Quantum communication

Quantum repeater

Bell-state analyzer

ABSTRACT

In optical quantum communication, quantum state measurement is necessary. This paper proposes a new technique for realization of polarization filter based on planar lightwave circuit (PLC). This filter is used for quantum state discriminator in quantum communication and also as a Bell-state analyzer in quantum repeater. Electro-optics interferometer has been used in design and implementation of polarization filter. We use lithium niobate as a wafer material and Ti:LiNbO₃ for waveguide. Two directional couplers have been used in this device. The length and spacing of these directional couplers have been designed so that each polarization is routed in specific output. The proposed device has one input and two outputs. If polarization of the input photon is vertical, then this photon will appear in output 1, otherwise if the input photon has horizontal polarization, it appears in output 2. For vertical polarization input, the power overlaps integral (POI) shows that isolation between two outputs is 14.96 dB. As to horizontal polarization input, the isolation between two outputs is 13.8 dB. The designed polarization filter has length of 33 mm and width of 60 μm. This device is very suitable for use in integrated optics.

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1. Introduction

Information processing nowadays is commonly implemented using quantities such as charges, voltages, or currents in electronic devices which operate on the basis of classical physics. Instead, quantum computing (QC) and more generally, quantum information processing (QIP) employ the laws of quantum mechanics for information processing. For such devices, corresponding building blocks are quantum bits (qubits) and quantum registers, and the basic gate operations are given by logical and coherent operations on individual qubits (single qubit operations) and controlled coherent interactions between two qubits (two-qubit operations) such that the state of the target qubit is changed conditional to the state of the controlling qubit.

Within the new fledgling field of quantum information [1], quantum communication has recently received much experimental attention. In the past years, entangled states have been used to experimentally demonstrate both dense coding [2,3] and teleportation [4–7]. Very recently, entanglement-assisted quantum cryptography has also been implemented using entangled photons [8–10]. While these schemes are realizable for moderate distances (up to a few kilometers in the case of cryptography), one is faced

with serious problems, if one wants to go beyond this distance scale. One of the problems is the absorption of photons in the transmission channel. Since quantum states cannot be copied [11], the only way to solve this is by sending large numbers of photons. Nevertheless, photons still seem to be the best quantum information carriers over long distances.

In quantum communication, qubits are sent across quantum channels that connect distant nodes of a quantum network. For distances much longer than the coherence length of a corresponding noisy quantum channel, the fidelity of transmission is usually so low that standard purification methods are not applicable. It is however possible to divide the channel into shorter segments that are purified separately and then connected by the method of entanglement swapping. Entanglement purification and swapping are two main parts of quantum repeater station. Quantum repeaters have been introduced in Ref. [12] as a concept for applying entanglement purifications and a nested connection of Einstein–Podolsky–Rosen (EPR) pairs [13] in order to overcome the problem of exponentially increasing error probabilities in the preparation of an EPR-entangled pair of separated particles via lossy channels.

Bell-state analyzer is used in quantum repeater and also in receiver and transmitter of quantum communication. Bell-state analyzer needs a device for distinguish Bell states in $|HV\rangle$ base. In linear optics realization of quantum repeater, Polarization beam splitter has been used for discern the Bell states. This paper will propose a new method for distinguish between the Bell states based on

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planar light wave circuit (PLC). A polarization filter will be designed and implemented by using PLC technique.

Standard versions of planar lightwave circuit (PLC) technology are well documented, and have been practiced since late-1980s. They combine significant features of optical fiber and integrated circuit technologies. Basically, light-guiding channels, similar in function to optical fibers, are defined on a silicon platform. These are fabricated by depositing sequential glass layers onto silicon wafers. Typically, an intermediate “core” layer with an elevated refractive index is patterned using photolithography and dry-etching. This patterned structure becomes the light-guiding channel. This baseline technology is well suited to the fabrication of passive devices such as couplers which depend on the proximity, controlled spacing and path lengths of parallel waveguides. Such PLC components are interfaced to fiber optic networks via edge attached fibers. This technology supports complex and versatile photonic integration. Implementation of quantum gates by using all optical circuits is very important in all optical communication networks. Since the trend for photonics integration is toward smaller and more densely packed components, it is necessary to be able to model these small components perfectly [14–16].

For the technological innovation of the optoelectronics field, the development of quantum photonic devices is important. The purpose of this paper is the feasibility search of new devices with the quantum optics function. The study is carried out based on theory and technology of PLC. Integrated optical quantum circuits based on chip-scale waveguide networks will likely find important applications in future quantum communication and computation. The proposed scheme aims to implement the required technology employing highly integrated optics devices rather than the more traditional bulk optics approach where one arranges individual optical elements on an optical table. This technique can be used for implementation of many components in quantum communication, not only filter. This approach avoids many of the problems that bulk optics suffers and also permits more general ways to code and manipulate information. We intend to explore the use of this novel technology for quantum information processing to develop novel methods for quantum information processing and to demonstrate the feasibility of basic quantum information processing in such arrangements.

In Section 2 we will briefly review the applications of polarization filter. Section 3 will give the main result of our work: we present a novel design of a polarization filter in a completely different physical mechanism. For the numerical simulation of the polarization filter, the beam propagation method (BPM) is used.

2. Application of polarization filter

Polarization filter is used for determine the quantum state of qubit. On the other hand we can use polarization filter in quantum measurement. Measurements as tunnels between the quantum and classical worlds play an important role. In transmitter part of quantum communication and also quantum repeater station, state measurement is necessary.

2.1. Quantum state discriminator in quantum communication

In quantum communication, quantum states are transferred from one station to another station. Let us denote the arbitrary quantum state of the particle to be teleported by $|\psi\rangle = a|0\rangle + b|1\rangle$. The operation of the teleporting device can be followed step by step in Fig. 1. First Alice and Bob share a $|\Phi^+\rangle = (1/\sqrt{2})(|00\rangle + |11\rangle)$ bell pair. To make it easier to follow the operation we refer to Alice’s quantum wires as A_1 and A_2 and to Bob’s half pair as B . The initial input joint state is

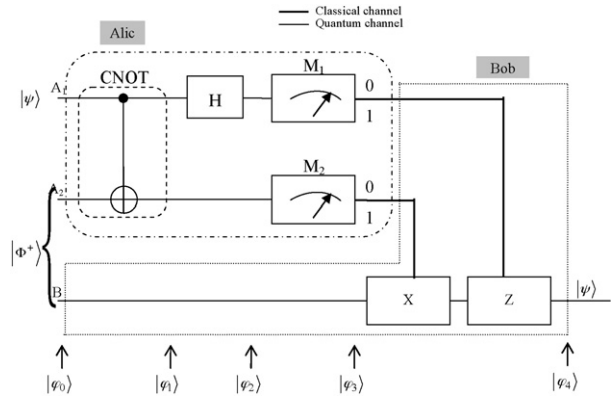


Fig. 1. Quantum communication protocol.

$$|\varphi_0\rangle = |\psi\rangle |\Phi^+\rangle = \frac{1}{\sqrt{2}} \left(a|0\rangle \left(|00\rangle + |11\rangle \right) + b|1\rangle \left(|00\rangle + |11\rangle \right) \right) \quad (1)$$

Next Alice applies a CNOT gate onto the qbits in her hands. However, instead of using matrix-vector operations we exploit the superposition principle that is a control with 0 leaves the data qbit unchanged while a 1 on the upper wire inverts the lower output. In order to highlight the modifications due to the CNOT gate we have the corresponding qbit (A_2):

$$|\varphi_1\rangle = \frac{1}{\sqrt{2}} \left(a|0\rangle \left(|00\rangle + |11\rangle \right) + b|1\rangle \left(|10\rangle + |01\rangle \right) \right) \quad (2)$$

The forthcoming Hadamard transform on the topmost quantum wire implements the well-known rule: $H|0\rangle \rightarrow (1/\sqrt{2})(|0\rangle + |1\rangle)$ and $H|1\rangle \rightarrow (1/\sqrt{2})(|0\rangle - |1\rangle)$ leading to

$$|\varphi_2\rangle = \frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}} \times \left[a \left(|0\rangle + |1\rangle \right) \left(|00\rangle + |11\rangle \right) + b \left(|0\rangle - |1\rangle \right) \left(|10\rangle + |01\rangle \right) \right] \quad (3)$$

Before performing the measurements Alice regroups the terms in $|\varphi_2\rangle$ according to her two qbits to produce a more readable form:

$$|\varphi_2\rangle = \frac{1}{2} \left[|00\rangle \left(a|0\rangle + b|1\rangle \right) + |01\rangle \left(a|1\rangle + b|0\rangle \right) + |10\rangle \left(a|0\rangle - b|1\rangle \right) + |11\rangle \left(a|1\rangle + b|0\rangle \right) \right] \quad (4)$$

Obviously Alice obtains one of the four possible two-bit results among 00, 01, 10 or 11 as measurement outcome. Each of them is in close connection with the state of Bob’s qbit hence Alice sends these two classical bits to Bob. After a short hesitation Bob compares $|\psi\rangle$ to the potential states of his half Bell pair. It is easy to realize the following relations:

$$A_1 A_2 \rightarrow B = U |\psi\rangle$$

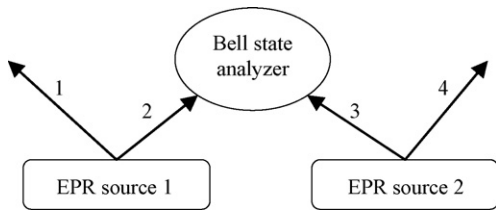


Fig. 2. Quantum entanglement swapping.

$$00 \rightarrow \frac{1}{2} (a|0\rangle + b|1\rangle) = I|\psi\rangle$$

$$01 \rightarrow \frac{1}{2} (a|1\rangle + b|0\rangle) = X|\psi\rangle$$

$$10 \rightarrow \frac{1}{2} (a|0\rangle - b|1\rangle) = Z|\psi\rangle$$

$$11 \rightarrow \frac{1}{2} (a|1\rangle - b|0\rangle) = ZX|\psi\rangle$$

where X and Z are bit-flip gate and phase-flip gate, respectively:

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \quad (5)$$

Therefore Bob has only to apply the inverse of the appropriate transform(s) in compliance with the received classical bits. Since our Bob read Part I carefully he knows that all these operators are unitary thus their inverses can be calculated simply by building their adjoint. Moreover it is easy to see that they are Hermitian too, which explains why the original gates are used in Fig. 1 as gates controlled by measurement results M_1 and M_2 . Thus finally Bob obtains the original $|\psi\rangle$.

This paper focuses on blocks M_1 and M_2 . These blocks should determine the quantum state of qubit. Depend on the polarization of photon; the output of M_1 and M_2 may be 1 or 0. Polarization filter is proposed for perform this measurement.

2.2. Bell state analyzer in quantum repeater

The bottleneck for communication between distant nodes is the scaling of the error probability with the length of the channel connecting the nodes. For channels such as an optical fiber, the probability for both absorption and depolarization of a photon (i.e., the qubit) grows exponentially with the length of the fiber. Quantum repeater is used for overcome these problems. Entanglement swapping and purification are performed in quantum repeater station. An important operation in quantum swapping and purification is Bell-state measurement.

A possibility to obtain entanglement is to make use of a projection of the state of two particles onto an entangled state. This projection measurement does not necessarily require a direct interaction between the two particles: when each of the particles is entangled with one other partner particle, an appropriate measurement, for example, a Bell-state measurement, of the partner particles will automatically collapse the state of the remaining two particles into an entangled state. This striking application of the projection postulate is referred to as entanglement swapping [17–19].

Consider two EPR sources, simultaneously emitting each a pair of entangled particles (Fig. 2). In anticipation of our experiments we assume that these are polarization entangled photons in the state:

$$|\psi\rangle_{1234} = \frac{1}{2} (|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2) \times (|H\rangle_3|V\rangle_4 - |V\rangle_3|H\rangle_4) \quad (6)$$

Here $|H\rangle$ or $|V\rangle$ indicates the state of a horizontally or a vertically polarized photon, respectively. The total state describes the fact that photons 1 and 2 (3 and 4) are entangled in an antisymmetric polarization state. Yet, the state of pair 1–2 is factorizable from the state of pair 3–4; that is, there is no entanglement of any of the photons 1 or 2 with any of the photons 3 or 4. We now perform a joint Bell-state measurement on photons 2 and 3; that is, photons 2 and 3 are projected onto one of the four Bell states which form a complete basis for the combined state of photons 2 and 3:

$$|\Psi^\pm\rangle_{23} = \frac{1}{2} (|H\rangle_2|V\rangle_3 \pm |V\rangle_2|H\rangle_3) \quad (7)$$

$$|\Phi^\pm\rangle_{23} = \frac{1}{2} (|H\rangle_2|H\rangle_3 \pm |V\rangle_2|V\rangle_3)$$

This measurement projects photons 1 and 4 also onto a Bell state, a different one depending on the result of the Bell-state measurement for photons 2 and 3. Close inspection shows that for the initial state given in Eq. (6) the emerging state of photons 1 and 4 will be identical to the ones photons 2 and 3 collapsed into. This is a consequence of the fact that the state of Eq. (6) can be rewritten as:

$$|\psi\rangle_{1234} = \frac{1}{2} (|\Psi^+\rangle_{14}|\Psi^+\rangle_{23} + |\Psi^-\rangle_{14}|\Psi^-\rangle_{23} + |\Phi^+\rangle_{14}|\Phi^+\rangle_{23} + |\Phi^-\rangle_{14}|\Phi^-\rangle_{23}) \quad (8)$$

In all cases photons 1 and 4 emerge entangled despite the fact that they never interacted with one another in the past. After projection of particles 2 and 3 one knows about the entanglement between particles 1 and 4.

The entanglement-swapping component of the quantum repeater is essentially nothing more than a Bell detector. It is well known that it is impossible to make a deterministic, complete, Bell measurement with linear optics but one can distinguish two out of four two-qubit Bell states with a simple beam splitter configuration.

A partial Bell measurement can be performed using a beam splitter. This is extensively described by Braunstein and Mann [20]. When two photons enter the beam splitter, one at each input, a detector coincidence in the two output modes collapses the input state onto $|\Psi^-\rangle$, that is, the singlet state. When both photons end up in one spatial output mode with opposite polarizations H and V, then the state is collapsed onto $|\Psi^+\rangle$. This paper proposes a new method for realization of Beam splitter based on PLC technique. This device is suitable for use in integrated optics.

3. Design and realization of polarization filter

An integrated optics polarization beam splitter will be proposed for realization of polarization filter. Beam splitter is a basic element of many optical fiber communication systems. We present a novel design of a polarization filter in a completely different physical mechanism. In linear optics quantum communication, polarization beam splitter is used as polarization filter. Because the dispersion relations of guide modes are different between horizontal and vertical polarization modes in PLC waveguides, we can create an integrated polarization filter by combining two PLC waveguides in which the guided modes within a certain frequency range are permitted for one polarization but forbidden for the other, with an input PLC waveguide in which both horizontal and vertical polarization can propagate. In our model, horizontal and vertical polarization modes are fed into the same input waveguides, and then separated into the two output waveguides.

Coupled mode theory is used in optical filters and switches. In these devices, two coupled waveguides that the coupling between

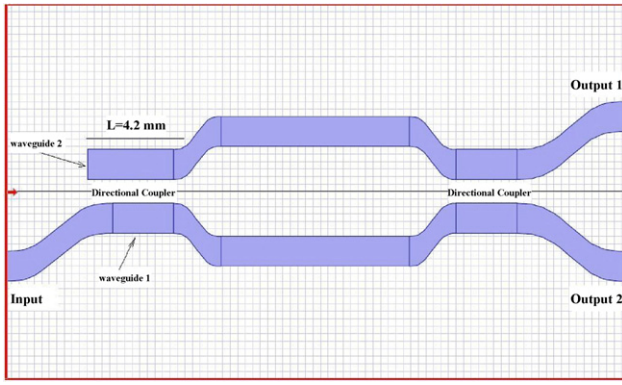


Fig. 3. Polarization filter as a quantum state discriminator.

them is controlled by their length and their separation are used. The waveguides are made from electro-optics material, that its permittivity is controlled by voltage. By controlling the permittivity, we can transfer power from one limb to another for another application.

The set of coupled differential equations that we just derive can be used to analyze transferred energy from one optical waveguide to another, when the guiding structures are brought into proximity. Consider two parallel waveguides, 1 and 2 in Fig. 3, for which the total field solutions can be written as linear combinations of individual waveguide modes:

$$\begin{aligned} E(x, y, z) &= a(z)E^{(1)}(x, y) + b(z)E^{(2)}(x, y) \\ H(x, y, z) &= a(z)H^{(1)}(x, y) + b(z)H^{(2)}(x, y) \end{aligned} \tag{9}$$

The amplitudes of $a(z)$ and $b(z)$ satisfy

$$\begin{aligned} \frac{da(z)}{dz} &= j\beta_a a(z) + jK_{ab} b(z) \\ \frac{db(z)}{dz} &= jK_{ba} a(z) + j\beta_b b(z) \end{aligned} \tag{10}$$

where K_{ab} and K_{ba} are the coupling coefficients. β_a and β_b are the propagation constants in waveguides 1 and 2, respectively. If at $z=0$, the optical power is incident only in waveguide 1, ($a(0)=1, b(0)=0$), we find:

$$|b(z)|^2 = \left| \frac{K_{ba}}{\psi} \right|^2 \sin^2(\psi z) \tag{11}$$

where $\psi = \sqrt{((\beta_b - \beta_a)/2)^2 + K_{ab}K_{ba}}$.

Therefore, at $\psi z = \pi/2, 3\pi/2, \dots, (2n+1)\pi/2$, the power transfer from guide 1 to guide 2 is maximum. If $\beta_a = \beta_b$, we have $\psi = |K_{ab}|$, and the solutions are

$$\begin{aligned} a(z) &= \cos Kz e^{j\beta z}, \\ b(z) &= j \sin Kz e^{j\beta z} \end{aligned} \tag{12}$$

where $K=K_{ab}=K_{ba}$, $\beta = \beta_a = \beta_b$, have been used. Complete power transfer occurs for synchronous coupling. For $Kl = (2n+1)\pi/2$, complete power transfer occurs; this is called a cross state. For $Kl = n\pi$, there is no power transfer from guide 1 to guide 2, which called a parallel state. If the length of coupler is $L = \pi/2K$, then the power of guide 1 transfers to guide 2 completely.

We use lithium niobate as a wafer material and Ti:LiNbO₃ for waveguides. Two directional couplers have been used in this device. The length and spacing of these directional couplers have been designed so that each polarization is routed in specific output. Fig. 3 shows the designed polarization filter.

4. Simulation results and discussion

For the numerical simulation of the polarization filter, the beam propagation method (BPM) is used. Fig. 4 shows the electric field pattern when the input waveguide is excited with vertical polarized incident light with frequency at 1300 nm. Fig. 5 shows the electric field pattern in the case of the incident light with horizontal polarization at the same frequency. The simulation completely agrees with our outlooks. The incident vertical polarized light propagates from input to output 1 almost with no fields in output 2 (Fig. 4).

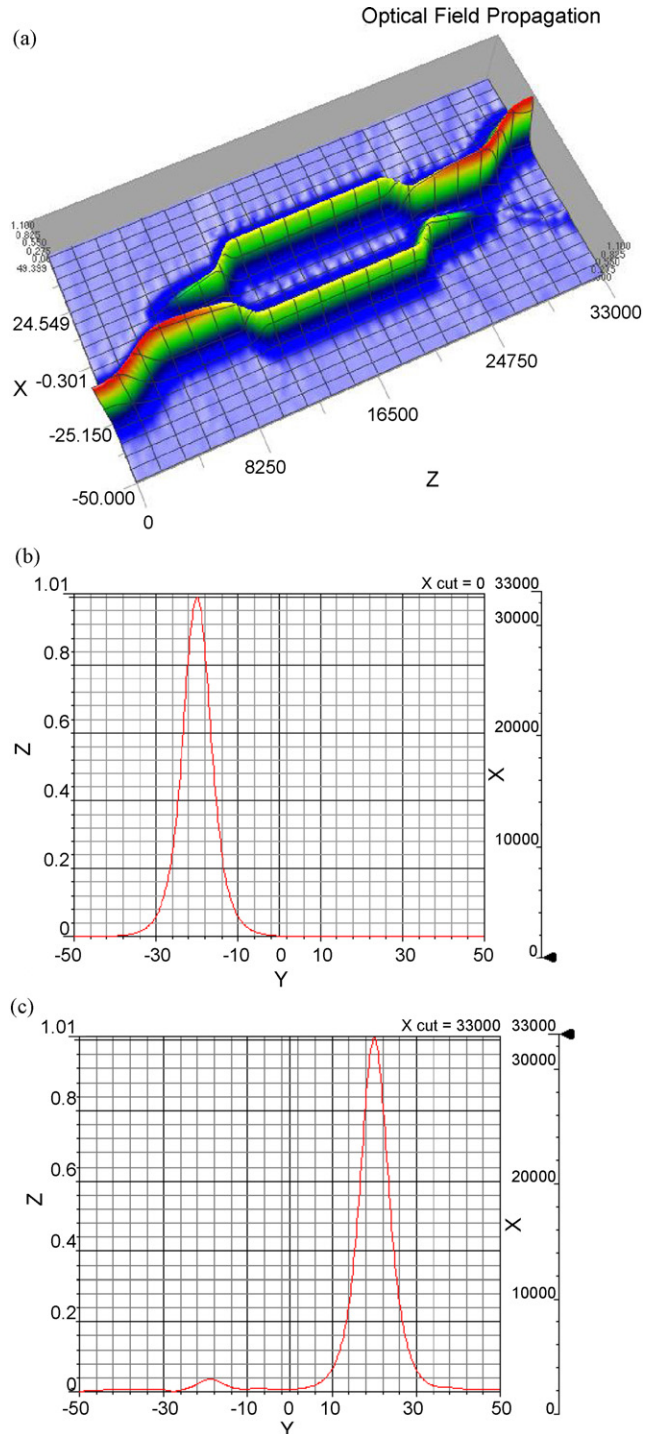


Fig. 4. Polarization filter with vertical polarized input: (a) optical field propagation, (b) input electric field profile, and (c) output electric field profile.

In the case of horizontal polarization as shown in Fig. 5, however, incident light travels through input and then only into output 2. Thereby a polarization beam splitter in the PLC is realized. In order to investigate the structure quantitatively, we numerically determine the contrast in power flow of the two output waveguides by calculating the flux through the observation line in the BPM simulations. For vertical polarization input, the power overlap integral (POI) in Fig. 6 shows that isolation between two outputs is 14.96 dB. As to horizontal polarization input, the isolation between two outputs is 13.8 dB.

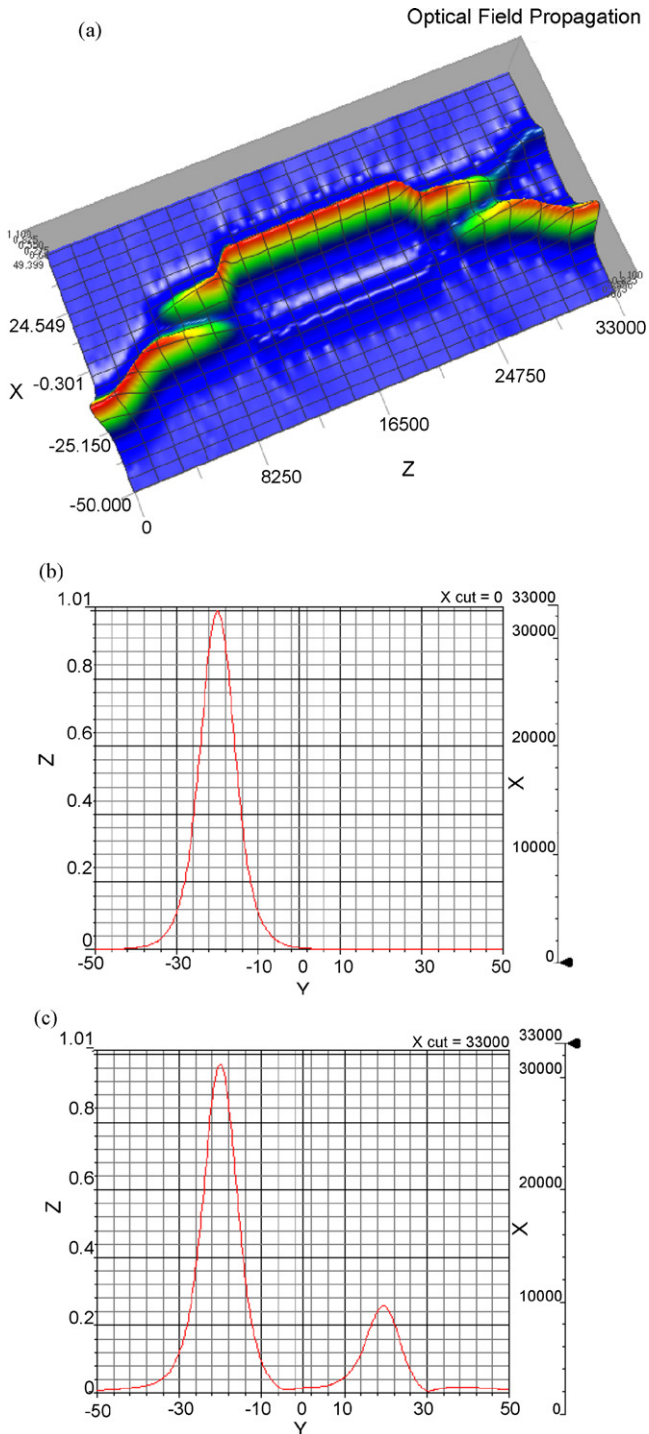


Fig. 5. Polarization filter with horizontal polarized input: (a) optical field propagation, (b) input electric field profile, and (c) output electric field profile.

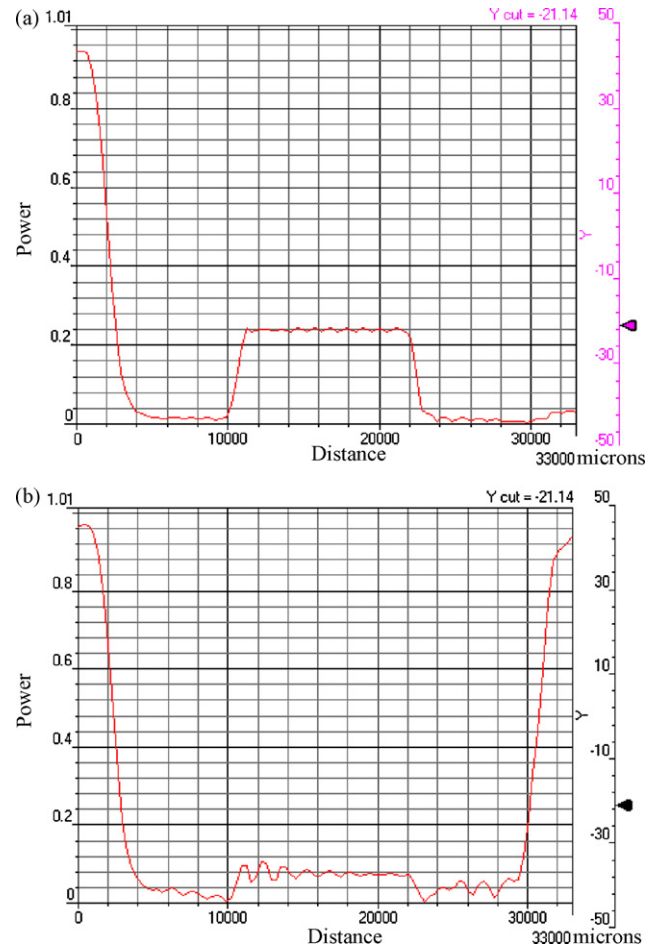


Fig. 6. Power overlap integral: (a) vertical polarized input and (b) horizontal polarized input.

Conventional glass polarization beam splitter (PBS) is used in the quantum communication scheme based on linear optics element on the optical tables. The proposed polarization filter is corresponding to PBS and suitable for use in integrated optical quantum circuits based on chip-scale waveguide networks will likely find important applications in future quantum communication and computation.

Future quantum technologies such as quantum communication and computation will require integrated optical circuits that offer high-fidelity and stability whilst enabling scalability. We exhibited that integrated optics offers the possibility of compact and stable components suitable for enabling quantum communication experiments. Our research demonstrated high-performance polarization filter for the first time in quantum integrated optics. This approach will enable the rapid development of sophisticated quantum optical circuits. This is a significant demonstration of the applicability of integrated optical technology to photonic quantum information treatment.

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