Four-stage cascaded variable optical attenuator with large attenuation range for quantum key distribution

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A four-stage cascaded variable optical attenuator (VOA) with a large attenuation range is presented. The VOA is based on a Mach–Zehnder interferometer (MZI) and fabricated in a silica-based planar lightwave circuit (PLC) platform. The thermo-optic effect is used to achieve intensity modulation. The measured maximum attenuation of the four-stage cascaded VOA is 88.38 dB. The chip is also tested in a quantum key distribution (QKD) system to generate signal and decoy states. The mean photon number after attenuation of the four-stage cascaded VOA is less than 0.1, which can meet the requirement of QKD.

Keywords: variable optical attenuator (VOA), silica, large attenuation range, thermo-optic effect

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1. Introduction

In recent years, quantum information technology, especially the quantum key distribution (QKD) system, has rapidly developed based on the powerful characteristics of quantum mechanics.[1,2] In commercial QKD systems, since a true single photon source is difficult to achieve, the usual practice is to use a variable optical attenuator (VOA) to attenuate a weak laser source to single photon levels. The VOA is typically the last device on Alice's side, which ensures that the transmitted signals are single photons, thus assuring the physical security of the system.[3,4] The quantum bit error rate of the system is closely related to the optical attenuation, and an attenuation of 70 dB–80 dB is required in practical applications.

Such a large attenuation range of dynamic modulation is difficult to achieve. A VOA based on a microelectromechanical system (MEMS) and free space is usually used in situations where large attenuation is needed.[5–9] For example, a MEMS VOA based on a vertical comb-drive achieved a dynamic range of 55 dB, and a free space VOA using frustrated total internal reflection obtained a dynamic range of 70 dB.[7,8] Other types of VOA with larger attenuation range have also been reported, such as an optofluidic VOA with an attenuation range up to 80 dB,[10] and liquid lens-based fiber VOAs demonstrate an attenuation range of 30 dB–40 dB.[11,12] However, all these kinds of VOA are bulky in size and are not suitable for integration. Although there are some improved designs, like silicon photonic MEMS VOAs employing a VOA in a silicon-on-insulator (SOI) wafer, which exhibits an attenuation range from 0 dB to 36 dB,[13] the fabrication process is complicated.

The on-chip VOA is the most attractive type that accords with the development trend of quantum and telecommunication networks. Various materials, like silica (SiO_2), silicon nitride (Si_3N_4), SOI, graphene, lithium niobite ($LiNbO_3$), and so on, are used in the PLC platform.[14–21] As far as we know, the attenuation range of the PLC-type VOAs is mostly within 20 dB–30 dB. Since the silica-based PLC has the most mature process technology, it is easy to realize mass production and integrate with other optoelectronic devices. The low loss, low power consumption, and good environmental stability can fully meet the requirements of quantum communication networks at the entire C-band (1530 nm–1565 nm).[22] The reported maximum attenuation range of a silica-based VOA is about 30 dB,[19] which is far lower than that required for a QKD system to generate single photon.

In this work, we propose a cascaded VOA based on a silica-based PLC platform. First, a single-stage VOA was designed based on the Mach–Zehnder interferometer (MZI) structure and using thermo-optic modulation. Then a four-stage cascaded VOA was fabricated, tested by a classical light source test system and a single photon source test system, and

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it was applied in the QKD system to produce single photons. The cascaded VOA proposed in this paper meets the large attenuation requirements of the QKD system.

2. Design and fabrication of the VOA

2.1. Design of the VOA based on an MZI

A silica-based PLC with a 0.75% refractive index difference was adopted. A rectangular waveguide with cross-sectional dimensions of 6 μm × 6 μm was used to meet the single-mode condition and reduce the transmission and bending losses. As seen in Fig. 1, on the silicon substrate, the core layer is surrounded by down-cladding SiO_2 and up-cladding boro-phospho-silicate glass (BPSG) on the silicon substrate.

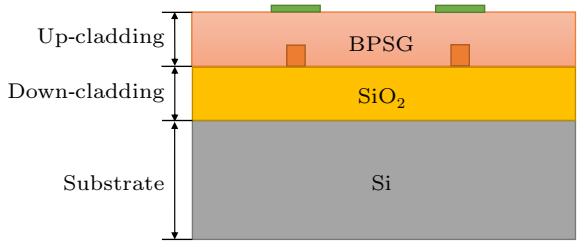


Fig. 1. The cross-section of the waveguide.

The VOA based on an MZI is displayed in Fig. 2, including the input/output ports, two 3-dB directional couplers in the coupling areas, and the modulation area which contains two transmission arms. The size of the device is calculated using the three-dimensional beam propagation method (3-D BPM). The waveguide gap and coupling length of the 3-dB directional coupler are 2.8 μm and 470 μm, respectively. The spacing between input/output ports is 127 μm to satisfy the coupling with the fiber array. Curved waveguides are essential in the device's layout, so the bending radius is set to 10000 μm to reduce the bending loss.

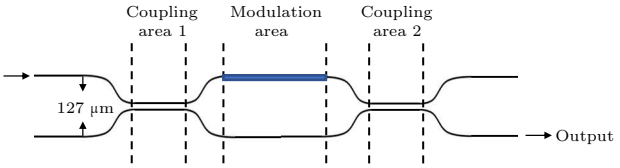


Fig. 2. Structural diagram of an MZI-based VOA.

When an optical signal with an amplitude of A_0 is incident on the input waveguide of the VOA, it will be split into two identical beams in the first coupling area and propagated on the two arms, respectively. In the modulation area, the thermo-optic effect is employed to regulate the refractive index difference between the two arms, thus introducing phase difference. After transmission in the modulation region, the two beams accumulate additional phases of φ_1 and φ_2, respectively. The light vector can be expressed as

$$E_1 = \frac{A_0}{\sqrt{2}} \exp\left[\mathrm{i}\left(\omega t + \varphi_1\right)\right], \tag{1}$$

$$E_2 = \frac{A_0}{\sqrt{2}} \exp\left[\mathrm{i}\left(\omega t + \varphi_2\right)\right]. \tag{2}$$

After interference in the second coupling region, the output power is determined by

$$\begin{aligned} I_{\text{out}} &= \frac{1}{2}\left|\frac{A_0}{\sqrt{2}} \exp\left[\mathrm{i}\left(\omega t + \varphi_1\right)\right] + \frac{A_0}{\sqrt{2}} \exp\left[\mathrm{i}\left(\omega t + \varphi_2\right)\right]\right|^2 \\ &= A_0^2 \cos^2\left(\frac{\varphi_1 - \varphi_2}{2}\right) = I_{\text{in}} \cos^2\left(\frac{\Delta\varphi}{2}\right), \end{aligned} \tag{3}$$

where I_{in} is the input power, and $\Delta\varphi = \varphi_1 - \varphi_2$ is the phase difference between the two beams of light transmitted in the two arms. The output power is a function of the phase difference. Therefore, the VOA can attenuate the light intensity by adjusting the refractive index of the modulation arms. Commonly used refractive index adjustment methods of on-chip structures include thermo-optic and electro-optic modulation. Thermo-optic modulation is chosen here because the amorphous SiO_2 material has electro-optic modulation and second-order nonlinear effects only after being polarized.[23] Furthermore, thermo-optic modulation is more suitable for large modulation ranges, while electro-optic modulation is for high-speed applications. The thermo-optic coefficient of SiO_2 at a wavelength of about 1550 nm is $\partial n/\partial T = 1.19 \times 10^{-5}$ K^{-1}, ensuring the thermo-optic modulation efficiency.[24] The phase difference caused by temperature change can be expressed as

$$\Delta\varphi = \frac{2\pi}{\lambda}\frac{\partial n}{\partial T}\Delta T L, \tag{4}$$

where λ is the operating wavelength, n is the refractive index, ΔT is the temperature change, and L is the modulation arm length. Ultimately, the output power is modulated by temperature fluctuation, as given by

$$I_{\text{out}} = I_{\text{in}} \cos^2\left(\frac{\pi \frac{\partial n}{\partial T}\Delta T L}{\lambda}\right). \tag{5}$$

2.2. Cascaded VOA

It is found that the attenuation range of a single VOA is less than 30 dB, which is not suitable for a QKD system. We proposed a four-stage cascaded VOA, which attenuates the light four times, significantly increasing the attenuation range. The structural diagram of the four-stage cascaded VOA is shown in Fig. 3. The four identical VOAs are numbered VOA-1, VOA-2, VOA-3, and VOA-4 from left to right, and the total chip size is 63 mm × 4 mm.

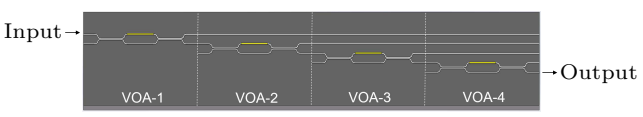


Fig. 3. Structural diagram of four-stage cascaded VOA.

After transmitting in the cascaded VOA, the output power is given by

$$I_{\text{out4}} = I_{\text{in1}} \cos^2\left(\frac{\pi \frac{\partial n}{\partial T} \Delta T_1 L}{\lambda}\right) \cos^2\left(\frac{\pi \frac{\partial n}{\partial T} \Delta T_2 L}{\lambda}\right) \times \cos^2\left(\frac{\pi \frac{\partial n}{\partial T} \Delta T_3 L}{\lambda}\right) \cos^2\left(\frac{\pi \frac{\partial n}{\partial T} \Delta T_4 L}{\lambda}\right). \quad (6)$$

According to the definition of attenuation,

$$\begin{aligned} \text{Loss} &= -10\log\left(\frac{I_{\text{out4}}}{I_{\text{in1}}}\right) \\ &= 10\log\left(\cos^2\left(\frac{\pi \frac{\partial n}{\partial T} \Delta T_1 L}{\lambda}\right) \cos^2\left(\frac{\pi \frac{\partial n}{\partial T} \Delta T_2 L}{\lambda}\right) \times \cos^2\left(\frac{\pi \frac{\partial n}{\partial T} \Delta T_3 L}{\lambda}\right) \cos^2\left(\frac{\pi \frac{\partial n}{\partial T} \Delta T_4 L}{\lambda}\right)\right), \end{aligned} \quad (7)$$

where I_{in1} is the input power and I_{out4} is the output power of the four-stage cascaded VOA. From Eq. (7), we can see that the longer the modulation length, the lower the power consumption. And the device size, L is set to 4000 μm.

2.3. Fabrication of the device

The designed cascaded VOA was fabricated in our laboratory. The SiO_2 down-cladding layer was formed on the Si substrate with a thickness of 625 μm by thermal oxidation. Then the core layer was deposited by plasma-enhanced chemical vapor deposition (PECVD). The layout of the device is transferred to the chip by photolithography, and the waveguide is etched by inductively coupled plasma (ICP). The up-cladding layer was deposited by PECVD, and the electrodes were fabricated by magnetron sputtering and tape stripping technology. The heating electrodes were located directly above the modulation arms to heat the waveguide.

The fabricated four-stage cascaded VOA was packaged as shown in Fig. 4. The input and output ports were coupled to single-mode fiber arrays, and the electrodes were wire-bonded to a printed circuit board.

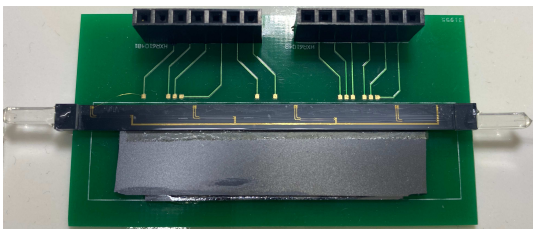


Fig. 4. The photograph of the packaged cascaded VOA.

3. Measurements and discussion

We measured the fabricated chip in a classical optical test system and a single-photon test system. For the classical optical test system, only the attenuation of a single VOA was tested because the attenuation of the four-stage cascaded VOA exceeded the detection limit of the system. In the single-photon test system, a large attenuation range can be obtained by the single-photon detector.

3.1. Classical optical test

The classical optical test system contains a tunable laser light source across the C + L band, a voltage source, a power meter, and a spectrometer. The performances of VOA-1, VOA-2, VOA-3, and VOA-4 were measured by applying a voltage to the 4 VOAs in sequence. We tested the attenuation of a single VOA over the operating wavelength range of 1530 nm to 1630 nm. It is demonstrated that the wavelength changes in the C + L band have no apparent effect on the performance of the VOAs. The response spectrum of the chip without applying current is displayed in Fig. 5, the insertion loss (IL) is less than 2 dB, and the loss non-uniformity is less than 1.2 dB from 1530 nm to 1630 nm.

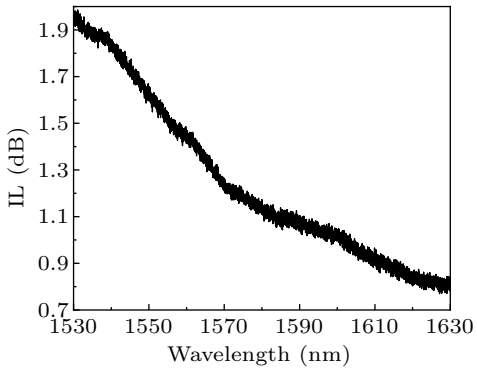


Fig. 5. Insertion loss of the four-stage cascaded VOA as a function of wavelength.

Currents were applied to the four VOAs separately, and the chip exhibited good wavelength insensitivity. The modulated attenuation as a function of current at 1530 nm, 1560 nm, 1590 nm, and 1630 nm is shown in Fig. 6. The attenuation range of a single VOA is more than 24 dB and the attenuation characteristics have little correlation with wavelength. However, the current values required by the four VOAs to achieve the maximum attenuation are not the same. To achieve maximum attenuation, the current applied to VOA-1 is about 55 mA, while that to VOA-2, VOA-3, and VOA-4 is about 58 mA, and the maximum attenuation value in the test results does not reach the designed maximum value. These differences are mainly caused by manufacturing errors in the modulation area, such as the deviation of the modulation arm length and the resistance of the heating electrodes.

If the effects of these four VOAs are superimposed, the total attenuation may exceed 100 dB. Since the ordinary photodetectors cannot detect light with an attenuation higher than 50 dB, it is necessary to use a single photon source test system to measure the maximum attenuation of the cascaded VOA.

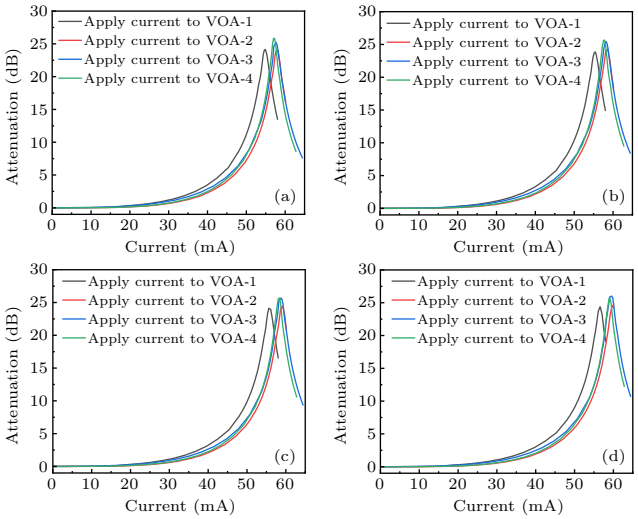


Fig. 6. Attenuation characteristics of the four-stage cascaded VOA at (a) 1530 nm, (b) 1560 nm, (c) 1590 nm, and (d) 1630 nm operating wavelengths when each VOA is individually energized.

3.2. Single-photon test

To further measure the total attenuation of the four-stage cascaded VOA, a single-photon test system was used, including a pulsed laser, a single-photon detector, and a direct-current source. For the pulse laser source, the frequency is 100 MHz, the pulse width is 500 ps, and the output power directly measured by a power meter is 52.25 μW. When the light is attenuated by the VOA, a single-photon detector is used to detect the light intensity. The photon number measured by a single-photon detector, called counts, is related to the optical power and can be expressed as

$$P = \frac{\text{counts} \times f}{10\%} h\nu, \tag{8}$$

where h is Planck's constant ($h = 6.626 \times 10^{-34}$ J·s), and ν is the photon frequency. f refers to the frequency of the pulsed light, which is 100 MHz here. 10% is the detection efficiency of the detector.

Firstly, we tested the attenuation characteristics of a single VOA by applying a voltage to VOA-1, VOA-2, VOA-3, and VOA-4 in turn, just like the classical optical test. By gradually increasing the applied voltage, the attenuation range of the VOA was measured at 1550 nm, and the influence of insertion loss of the four-stage cascaded VOA was subtracted. To highlight the overall effect of the four-stage cascaded VOA, we overlay the individual test results of the four VOAs, as shown in Fig. 7(a). The test results indicate that when VOA-1 is loaded with a current of 55.11 mA, the attenuation of VOA-1 reaches a maximum value of 24.01 dB. Similarly, when VOA-2 is loaded with a current of 58.14 mA, the attenuation of VOA-2 reaches a maximum value of 24.26 dB. When VOA-3 is loaded with 57.92 mA, the attenuation reaches the maximum value of 25.34 dB. When VOA-4 is loaded with 57.54 mA current, the attenuation reaches the maximum value of 25.91 dB. In the measurements, the current applied to reach the maximum attenuation varies slightly for different VOAs, which is consistent with the classical optical test results.

Substituting the maximum attenuation value obtained from the single-photon test into Eq. (7) gives the relationships between the attenuation of the four VOAs and the temperature rise as shown in Fig. 7(b). The maximum attenuation values of VOA-1, VOA-2, VOA-3, and VOA-4 are 24.01 dB, 24.26 dB, 25.34 dB, and 25.91 dB respectively, and the corresponding temperature rises are 15.63 °C, 15.65 °C, 15.72 °C, and 15.76 °C respectively. The maximum modulation efficiency can be achieved with a temperature rise of about 15 °C. As can be seen from Fig. 7, the test results are basically consistent with the change trend calculated by the formula.

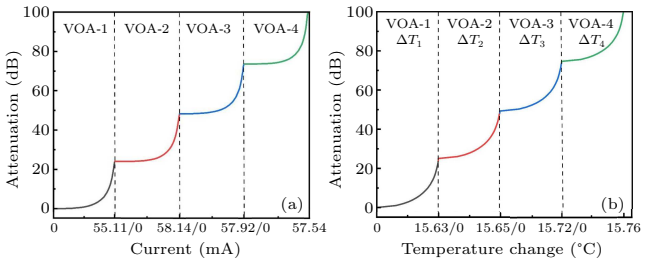


Fig. 7. (a) The relationship between the measured attenuation of each VOA and the applied current, and (b) the relationship between the attenuation and the theoretical temperature change.

A test of multiple VOAs working simultaneously was carried out. When all four VOAs are powered on, the total attenuation can reach a maximum of 88.38 dB which can meet the requirements of the QKD system. However, it is found that the total attenuation of the four-stage cascaded VOA is not simply equal to the superposition of attenuation values of individual VOAs. In the chip layout, to eliminate the effect of the electrodes on the symmetry of the two arms of the MZI, although only one arm needs to be modulated, both arms are covered with heating electrodes. The common negative electrode is located below the VOA, which will cause the temperature of the non-modulated arm to rise, thereby reducing the modulation efficiency.

3.3. Test in a QKD system

The prepared four-stage cascaded VOA was applied to a QKD system to randomly generate the signal state and decoy state on Alice's side. Taking the BB84 time-bin phase encoding protocol with a decoy state as an example, as shown in Fig. 8, the test system includes a 1550 nm pulsed laser that can emit an optical pulse with a pulse width of 500 ps and a frequency of 100 MHz, an asymmetric Mach–Zehnder interferometer (AMZI) with thermo-optic phase modulators (TOPM) on the two arms, and a single-photon detector. And the fabricated four-stage cascaded VOA is placed at the output of Alice.

In the test system, the optical pulses pass through the AMZI with an arm length difference of 400 ps. Then the pulse is split into two pulses that are coherent. The TOPM on one

arm modulate the phase of the pulses, thus encoding the qubit state. The four-stage cascaded VOA will attenuate the light intensity to obtain the desired mean photon number of the output pulse. As we use weak coherent pulses, the decoy state method is used to prevent photon number splitting attacks. The encoded pulse is randomly attenuated to two intensities with mean photon numbers μ_1 and μ_2, called the signal state and the decoy state.[25] In a one-decoy state protocol, the mean photon number of a decoy state is much lower than that of the signal state, so $\mu_2 = \mu_1/2$ is set in this work.

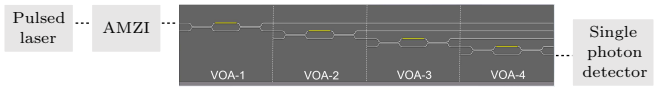


Fig. 8. Structure diagram of a QKD transceiver system based on a PLC platform.

Figure 9 shows the superposition state when the phase difference between the first pulse and the second pulse is 0 and π, respectively. And the signal state and the decoy state are formed by attenuation to different average photon numbers. The counts per second of the signal state are 66×10^4, and the mean photon number in each pulse is 0.066. The counts per second of the decoy state are 33×10^4, and the mean photon number in each pulse is 0.033. The corresponding attenuations of the four-stage cascaded VOA are 77.91 dB and 80.9 dB for the signal state and the decoy state. The test shows that the four-stage cascaded VOA proposed in this paper can make the mean photon number in each pulse of the quantum state less than 0.1, which meets the requirements of the QKD system.

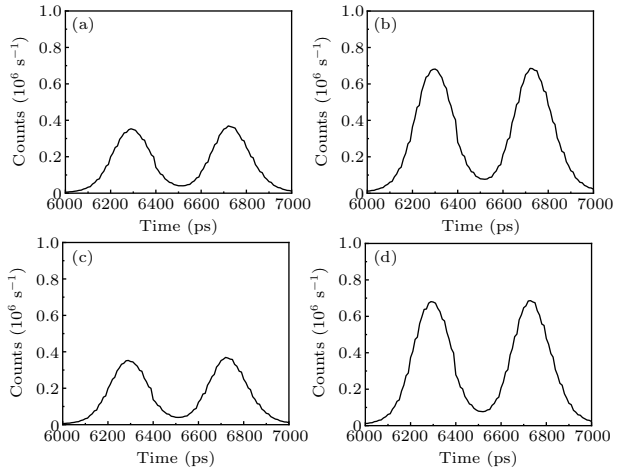


Fig. 9. The attenuated superposition quantum state generated. (a) A decoy state with phase difference of 0, (b) a signal state with phase difference of 0, (c) a decoy state with phase difference of π, and (d) a signal state with phase difference of π.

4. Conclusion

In this paper, a four-stage cascaded VOA with a large attenuation range based on a silica-based PLC platform has been designed and experimentally demonstrated. The test results of classical light sources show that the attenuation of each VOA in the cascade structure is greater than 24 dB in the C+L band with good uniformity. Single-photon source test results show that the maximum attenuation of the four-stage cascaded VOA can reach 88.38 dB, which meets the 70 dB–80 dB attenuation requirement of the QKD system. We also apply the chip to the QKD system using the BB84 time-bin protocol to prepare the signal state and the decoy state. The average photon numbers of the signal state and the decoy state are 0.066 and 0.033, respectively. This four-stage cascaded VOA is suitable for most QKD systems.

Acknowledgments

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