Observation of high contrast ratio asymmetric transmission for linearly and circularly polarized waves

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Keywords: asymmetric transmission, contrast ratio, polarization conversion, selective transmission

Abstract
Asymmetric transmission of light has important applications in integrated photonic systems for communications and information processing. Various Lorentz-reciprocal devices have been explored to achieve asymmetric transmission. However, the contrast ratio is limited. Here we show that the asymmetric transmission of linearly polarized and circularly polarized waves can both be achieved by combining polarization conversion and selective transmission. What is perhaps most important here is that the proposed asymmetric transmission devices for operation at wavelength 633 nm experimentally display asymmetric transmission with contrast ratio exceeding 37 dB and 34 dB for linearly polarized wave and circularly polarized wave, respectively. The high contrast ratios are much higher than previous results in published literature. The proposed reciprocal approach holds promising for utilization in integrated photonic systems.

1. Introduction
Realizing asymmetric transmission (AT) of electromagnetic wave is important because it has potential applications in integrated photonic systems for communications and information processing [1–10]. Traditionally, AT can be achieved by using magneto-optical materials and nonlinear materials, which are respectively break Lorentz-reciprocal and time inversion symmetry [11–15]. However, the former method usually needs a large external magnetic field to produce the magneto-optical effect in materials and the size of the system is big, which is not compatible with the integrated technology. It has been reported that the AT with contrast ratio 40 dB could be realized by using the nonlinearity of silicon [16]. Nevertheless, this method usually needs a strongly powered incident beam to induce nonlinearity [16, 17].

Besides, realizing AT in reciprocal devices has recently become a thriving research topic because it neither need externally applied fields, nor has limitation on the intensity of incident light [18–25]. Examples are the AT devices designed in [18], which have unique advantages such as small footprint and passive operation, and high contrast ratio of 15.3 dB. The contrast ratio, which is the most important parameter to measure the performance of AT devices, is largely smaller compared with that presented in [16]. Therefore, it is of great significant to improve the contrast ratio in reciprocal AT devices.

Besides, most of the AT approaches are only for linearly or circularly polarized waves. It is highly desirable to have an approach that can achieve AT for both linearly and circularly polarized waves [26].

Here, we proposed the combination of polarization conversion and selective transmission to realize AT for both linearly polarized waves and circularly polarized waves. The device of AT for linearly polarized wave is mimicked by one half-wave plate (HWP) and one linearly polarizer (LP), and that for circularly polarized wave is mimicked by two quarter-wave plates (QWPs) and one LP. The theoretically analysis based on Jones matrix shows that the contrast ratio tends to infinity in principle. The experimentally results show that the AT devices display efficient asymmetric optical transmission with contrast ratios exceeding 37 dB and 34 dB, respectively, which are much higher than those in the published literature [18]. It is noted that the size of the asymmetric transmission can be greatly reduced, since HWP, LP, and QWP can be constructed with thin metasurfaces.
2. Theory

The AT device for linearly polarized waves is shown in figure 1(a), consisting of one HWP and one LP. If the incident light is transverse magnetic (TM) wave, then the Jones matrix is \( \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \). The relative rotation between the plane of incidence and the fast axis of the HWP is \( 45^\circ \). Passing through the HWP, the transmitted wave can be expressed as

\[
\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}
\]

(1)

After passing through the LP, the transmitted wave can be expressed as

\[
\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}
\]

(2)

Theoretically speaking, the transmission in the forward direction can be close to unity. From the opposite direction, after the light goes through the LP, the transmission of incident TM wave is

\[
\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}
\]

(3)

Therefore, the light cannot pass the structure in the opposite direction, resulting in near-zero transmission. As a result, efficient asymmetric transmission can be achieved, and the contrast ratio tends to infinity in principle. The proposed structure is also can be used to achieve AT for transverse electric (TE) wave, and the Jones matrix is also can be employed to analyze the mechanism.

For circularly polarized wave, the asymmetric transmission device is constructed by a LP sandwiched with two QWPs, as shown in figure 1(b). The relative rotation between the plane of incidence and the fast axes of the QWPs is \( 45^\circ \). If the incident light is right circularly polarized (RCP) wave, then the Jones matrix is \( \frac{\sqrt{2}}{2} \begin{pmatrix} 1 & -j \\ j & 1 \end{pmatrix} \). Passing through the first QWP, the transmitted wave can be expressed as

\[
\frac{\sqrt{2}}{2} \begin{pmatrix} 1 & -j \\ -j & 1 \end{pmatrix} \frac{\sqrt{2}}{2} \begin{pmatrix} 1 \\ -j \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}
\]

(4)

After passing through the LP, the transmitted wave can be expressed as

\[
\frac{\sqrt{2}}{2} \begin{pmatrix} 1 & -j \\ -j & 1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \frac{\sqrt{2}}{2} \begin{pmatrix} -j \\ 1 \end{pmatrix}
\]

(5)

Note that the amplitude of the transmitted wave will not change after passing the second QWP. Consequently, the transmission is unity in this direction. From the opposite direction, when the light goes through the QWP, the transmission of incident RCP wave is

\[
\frac{\sqrt{2}}{2} \begin{pmatrix} 1 & j \\ j & 1 \end{pmatrix} \frac{\sqrt{2}}{2} \begin{pmatrix} 1 \\ -j \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}
\]

(6)

According to equation (3), the transmitted wave cannot pass the behind LP, and thus the transmission in the opposite direction is close to zero. The proposed structure is also applied for left circularly polarized (LCP) wave, and the analysis is similar. From the analysis based on Jones matrix, one can see that the combination of
polarization conversion and selective transmission can be used to achieve asymmetric transmission for both linearly polarized waves and circularly polarized waves. More importantly, the contrast ratio tends to be infinity in principle.

3. Experiment

The experimental setup for asymmetric transmission of linearly polarized wave and circularly polarized wave are respectively shown in figures 1(a) and (b). The optical fiber laser can emit linearly polarized wave at wavelength 633 nm, and the optical power is about 1.5 mW. One HWP and one LP are installed in one pillar. The angle between the plane of incidence and the fast axis of the HWP is 45°. The transmission measurement in two opposite directions can be realized by just rotating the pillar with an angle of 180°. The optical power meter (OPM) is used to collect the intensity of the transmitted wave. For AT of circularly polarized wave, two QWPs and one LP are installed in one pillar. The experiment is similar for linearly polarized wave, except that there is one QWP between the laser and the sample. The angle between the plane of incidence and the optical axes of the QWPs is 45°. The experiments for linearly and circularly polarized waves are carried out three times.

4. Results and discussion

The experimental results for linearly polarized wave are shown in figure 2. The average transmission for the forward direction and the backward direction is respectively 0.787 and 0.142 × 10⁻³. The smallest contrast ratio is 37.3 dB, which is much higher than that in [18]. The difference between the biggest and the smallest contrast ratio is small than 1%, indicating the experimental results are reliable. The reason why the transmission in the forward direction is below than 0.8 is that the reflection and absorption of the LP cannot be ignored. We have tested the transmission of single LP three times, and the average transmission is 0.795. The transmission in the forward direction can be further enhanced if antireflection coating is added.

The experimental results for circularly polarized wave are shown in figure 3. The average transmission for the forward direction and the backward direction is respectively 0.755 and 0.206 × 10⁻³. The smallest contrast ratio is 34.6 dB. The difference between the biggest and the smallest contrast ratio is small than 6%, indicating the experimental results are relatively reliable. The reduced transmission in forward direction is also attributed to the reflection and absorption of the LP.

The fabrication of LPs, HWPs, and QWPs is very mature, and thus the fabrication of the combined structure of them should not be a problem. Especially, with the development of metasurfaces, many LPs, HWPs, and QWPs can be designed with extremely thin size [27, 28]. We believe that the size of the proposed structure in this paper can be greatly reduced if metasurfaces are used.

5. Conclusions

Using Jones matrix, we have theoretically proved that asymmetric transmission of both linearly polarized and circularly polarized waves can be achieved by combing polarization conversion and selective transmission. In
addition, we have used commercial linearly polarizers, half wave plates and quarter wave plates to mimic the asymmetric transmission devices, and the asymmetric transmission for linearly and circularly polarized waves are observed. Most importantly, the contrast ratios for linearly polarized and circularly polarized waves are respectively 37.3 dB and 34.6 dB, which are much higher than previous results. We believe that the asymmetric transmission devices designed in this work appear promising for use in integrated optical systems.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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