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Silicon Brewster plate wavelength separator for a mid-IR optical parametric source

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Abstract: The availability of optical elements for the mid-infrared wavelength range, such as polarizers and wavelength separators, is limited especially when a broadband wavelength range coverage is required. We propose a polarizer based on uncoated silicon Brewster plates. A detailed analysis of the polarizer's contrast and the influence of parasitic reflections, its dependence on wavelength and the angular misalignment is shown. Two different arrangements of the two and four-plate polarizer are discussed. With contrast including the influence of parasitic reflections of over 10^3 for the whole transparency range of silicon ($1.2 - 6.5 \mu\text{m}$), the four-plate polarizer is an effective, low-cost, high-power compatible tool providing sufficient contrast for signal and idler beam separation of the broadband mid-infrared type II optical parametric sources. The proposed polarizers can function as an attenuator assembly without any waveplate.

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1. Introduction

The mid-infrared (mid-IR) wavelength range ($2 - 8 \mu\text{m}$) offers a wide variety of applications in many different fields. Infrared atmospheric windows - areas of wavelengths transmittable through the atmosphere without absorption, necessitate the use of lasers that generate radiation in these specific areas. These lasers then serve as tools for communication, atmospheric diagnostics and LIDARs [1]. On the other hand, the absorption of the mid-IR radiation in various materials is also beneficial, determining its use in medicine and industry. Typical medical and surgical applications of these lasers are in ophthalmology, micro-surgery, dermatology, urology and dental surgery [2]. In industry, mid-infrared lasers are used as tools for polymer processing [3]. Mid-IR ultrashort pulses are also used for high harmonics generation and for particle acceleration [4].

Currently, the sources of coherent mid-IR generation are solid-state lasers, quantum cascade lasers, and wavelength down-conversion systems based on nonlinear optical processes. Availability of optical elements such as polarizers is limited especially when they should operate over a broadband wavelength range. An example of a source, which needs ultra-broadband optical elements, is the picosecond, high-power mid-IR source based on optical parametric conversion under development at the HiLASE Centre [5, 6, 7]. It consists of an optical parametric generator (OPG) followed by an optical parametric amplifier (OPA), both pumped by a beam of an Yb:YAG thin-disk laser, delivering 90 W of average power at 93 kHz pulse repetition rate, 1030 nm wavelength and pulse duration down to 1.3 ps. The OPG stage is based on a double pass down-conversion taking place in a periodically poled LiNbO₃ crystal. The OPA stage consists of a pair of KTA crystals, used in a type II collinear interaction, where the signal and the idler beams have perpendicular polarization. The tuning range for the signal is from 1.52 to 1.98 μm and idler tunability spans the range from 2.15 to 3.2 μm . Such a broad tunability is very desirable for practical uses, but it causes a difficulty in separating the signal

and idler beams. Ultra-broadband wavelength separators based on dielectric thin films are difficult to design and manufacture. Moreover, they are high-priced. Thus, a different solution for mid-IR beams separation is required.

In this paper, we present an overview of polarizers currently used in the mid-infrared region. In response to the scarcity of polarizers suitable for separation of perpendicularly polarized signal and idler beams of type II mid-IR parametric sources, we propose a silicon Brewster plate polarizer providing contrast over 10^3 in the whole transparency range of silicon ($1.2 - 6.5 \mu\text{m}$). A detailed analysis of the polarizer's contrast, its dependence on wavelength and angular misalignment, is shown for two different arrangements of the two and four-plate polarizer: pile of plates (parallel) and beam-displacement compensating. A detailed overview of the influence of the parasitic reflections of the *s*-polarized beam on the overall contrast of the polarizer is also presented. The four-plate polarizer has been proven to serve as an effective, low-cost, high-power compatible tool that provides sufficient contrast for signal and idler beam separation of the broadband mid-infrared source. As a response to the scarcity in broadband half-wave plates, the proposed polarizer can function as waveplate-free attenuator assembly in the whole transparency range of silicon.

2. Polarizers for the mid-infrared

Polarizers in the mid-infrared can be divided into several categories: polarizing prisms, polarizing beam-splitters, wire-grid polarizers and reflection or transmission Brewster type polarizers. The overview provides information about the transparency range, which is related to the substrate materials, and the contrast ratios, i.e. ratios of maximum to minimum transmission of a linearly polarized input beam.

Polarizing prisms made of birefringent materials exist in a wide variety of designs and are usually made of calcite [8, 9]. While its very high birefringence (ordinary refractive index $n_o = 1.66$, extraordinary refractive index $n_e = 1.49$) makes it highly suitable for use in these types of polarizers, its transparency unfortunately reaches only up to $\sim 2500 \text{ nm}$ [8, 9]. Other materials, whose transparency exceeds that of calcite in the mid-IR region are e.g. MgF_2 , CdSe , and sapphire. However, their low birefringence also lowers the angular acceptance, which is important for most practical uses. Rutile (TiO_2) polarizing prisms transparent over the range from 2.2 to $4 \mu\text{m}$ are commercially available, but only in small sizes (5 mm or 8 mm aperture, contrast ratio $100\,000:1$) [9, 10]. Another suitable material is the well-known YVO_4 , with high transmittance from approximately 400 nm up to $3.8 \mu\text{m}$ and a high birefringence of about 0.2 in the whole transparency region [11].

Wire-grid polarizers consist of an array of thin metal wires closely spaced upon a transparent substrate. The separation between the wires must be less than the wavelength of the incident radiation. In addition, the width of each wire should be small compared to the spacing between them. The wave transmitted through the wire-grid polarizer is linearly polarized with an electric field that is completely perpendicular to the wires [12]. Wire-grid polarizers suitable for use in the $2 - \sim 30 \mu\text{m}$ range, are based on BaF_2 or ZnSe substrates and can provide contrast around 80 or 5000 , respectively [13], or KRS-5, providing a 99.9% degree of polarization [14].

Reflection Brewster polarizers utilize the fact, that the light reflected from a plate placed under Brewster's angle of incidence, is completely *s*-polarized. The incident surface of the plates can be coated or uncoated. In the uncoated case, the *s*-polarization has limited reflectivity which causes significant losses. The main disadvantage of these polarizers, compared to the previously mentioned options, is their larger size. In addition, multiple reflections between input and output faces, which lower the contrast of the polarizer, occur on the uncoated plates of these types of polarizers, but can be eliminated by either wedging the plates or covering the back-surfaces with absorptive coating [15].

These polarizers are most often used in the so-called K-geometry, or the chevron geometry (see Fig. 1). The K-geometry polarizer inverts the beam because of three reflections. Tilting

the input beam relative to the K-geometry polarizer optic axis deviates the beam. These alignment effects do not exist in the chevron geometry. [16]

The most common materials for reflection-type Brewster polarizers are high refractive index materials, such as germanium (Ge), selenium (Se) and silicon (Si). In a Ge-based polarizer utilizing a single external reflection, the degree of polarization was 99 % from 1.1 to 2.3 μm [16]. In a large aperture polarizer, whose arrangement was identical to the chevron geometry in Fig. 1, with two or four reflections from deposited selenium on roughened back-side glass plates, the degree of polarization in the visible was 99.9% [17]. In the case of a K-type arrangement with reflection from two Al mirrors, and one polished Si plate with roughened back side, the degree of polarization was 99 % at 10.6 μm [18].

Fig. 1. Chevron (top) and K-geometry (bottom) reflection-type Brewster plate polarizer. P - plate of a given material, M - mirror [10].

Pile of plates polarizers or, in other words, transmission Brewster polarizers, utilize a placement of several plates under Brewster's angle (Fig. 2). The reflectance of a p -polarized wave on a single surface equals zero and the transmittance of the polarizer for the s -polarized component can be expressed in terms of refractive index and the number of plates. However, multiple reflections, which can even interfere, occur inside or between the plates. Parallel arrangement of the plates causes a displacement of the original beam (Fig. 2a), which can be removed by utilizing a beam-displacement compensating (or antiparallel) arrangement (Fig. 2b, 2c).

Fig. 2. Beam (orange arrows) propagation through a polarizer consisting of a) parallel arrangement of two Si plates (blue), b) beam-displacement compensating arrangement of two Si plates c) beam-displacement compensating arrangement of four Si plates. The performance of the topologies in b) and c) were studied experimentally.

An extensive overview of the pile of plates polarizers, as well as Brewster angle reflection polarizers has been done by Bennet in [8] and [19]. Materials, that have been used for mid-IR pile of plates polarizers, were Se (6 plates, degree of polarization up to 99 % in the 2.5 – 25 μm region [20]), ZnSe (6 plates, extinction ratio of 800 at 4 μm [8]), AgCl (6 wedged plates, degree of polarization up to of 99 % [21]), thallium bromide KRS-5 [22], polyethylene (15 films, degree of polarization 98 % at 10.6 μm [23]), and germanium (3 plates, 2 wedged, extinction ratio 898 [24]). As suggested by Bird and Shurcliff in [21], the multiple reflections can be removed by spreading the plates in a fanned manner. Internal reflections within the plates can be reduced

by wedging the plates [21]. Note that wedging the plates can be inconvenient for broadband sources due to the dispersion. The overview of advantages and disadvantages of all presented polarizer types is shown in Tab. 1.

Tab. 1 Overview of the advantages and disadvantages of polarizer types presented in chapter 2

Type of polarizer	Advantages	Disadvantages	Commercial availability
Polarizing prism	Either high birefringence or high mid-IR transparency can be ensured at the same time	mid-IR transparency can be	Yes
Wire-grid	Wide transparency	Higher cost	Yes
Reflection Brewster	Wide material selection in the mid-IR, high degree of polarization, low cost	Bulky, requires a reflective component (mirror) and often multiple reflections, parasitic reflections in the s -polarization from parallel plates	No, however materials are commercially available, and the polarizer setup can be custom-made for the specific application, contrast, and wavelength range requirements
Transmission Brewster	Wide material selection in the mid-IR, high contrast, low-cost, no need for a reflective component, anti-parallel setup does not cause beam deviation	Bulky, multiple plates required, parasitic reflections in the s -polarization from parallel plates	

3. Silicon Brewster plate-polarizer for the mid-infrared broadband source

Overall, finding a low-cost broadband polarizer, providing high extinction ratio in mid-IR region is not an easy task. A suitable material is silicon, whose transmission covers most of the mid-IR range and which is commercially available at low cost in both plates and wafers for the optical and semiconductor industry. The use of a transmission silicon Brewster plate polarizer was considered in [8]. The paper concentrated on comparison of the properties of a p -type and n -type Si wafers in a pile of plates arrangement. Measurements reported in this publication indicate 100 % transmission of the p -polarized component, with angular misalignment tolerance $+3.04^\circ$, -3.80° for 1 % loss in the p -wave transmission for a collimated beam. Parasitic reflections in the s -polarization were reported. In this paper, we study the alignment sensitivity in large detail for different arrangements of the plates. Moreover, we significantly extend the usefulness of the polarizers.

For the design of the Brewster plate polarizer, silicon plates are proposed. Silicon is highly transparent in the range from $1.2 \mu\text{m}$ to $\sim 6.5 \mu\text{m}$. Further in the text we will concentrate on this wavelength range. Note that if partial absorption is acceptable, the silicon polarizer usage up to wavelength of $\sim 250 \mu\text{m}$ can be considered [9]. The dependence of the silicon refractive index n [25] and Brewster's angle $\theta_B = \arctan(n(\lambda))$ on wavelength is shown in Fig. 3. High $n \sim 3.45$ results in high θ_B of $\sim 73.9^\circ$. The R_s' and R_p' for one interface can be calculated according to Fresnel's equations Eq. 1 and Eq. 2, where θ is the angle of incidence, and are presented in Fig. 3 inset. The transmittance of the p , or s -polarized component through one interface can be then calculated as $T_i' = 1 - R_i'$, where i stands for s or p -polarization. High n is also responsible for the high reflectivity of the s -polarized component R_s' of ~ 72 % for single silicon/air interface at θ_B . This obviously results in high contrast $T_p:T_s$, achievable with few plates only, because the transmission of s polarization through a single plate (i.e. two interfaces) is ~ 8 %. The contrast of a k -plate polarizer can then be calculated by equation Eq. 3, where k is the number of the plates and $2k$ indicates passage of the beam through two interfaces of one plate. Later in the text, where a T_p or T_s of a k plate polarizer is mentioned, it therefore refers to the total transmittance through $2k$ interfaces.

Fig. 3. Dependence of index of refraction and Brewster's angle of silicon on wavelength. Inset shows the dependence of transmittance and reflectance of p and s -polarized components on incidence angle.

$$R'_s = \frac{\left| n_1 \cos \theta - n_2 \sqrt{1 - \left(\frac{n_1 \sin \theta}{n_2} \right)^2} \right|^2}{\left| n_1 \cos \theta + n_2 \sqrt{1 - \left(\frac{n_1 \sin \theta}{n_2} \right)^2} \right|^2} \quad (1)$$

$$R'_p = \frac{\left| n_1 \sqrt{1 - \left(\frac{n_1 \sin \theta}{n_2} \right)^2} - n_2 \cos \theta \right|^2}{\left| n_1 \sqrt{1 - \left(\frac{n_1 \sin \theta}{n_2} \right)^2} + n_2 \cos \theta \right|^2} \quad (2)$$

$$(T_p : T_s)_{k\text{-plates}} = \left(\frac{T'_p}{T'_s} \right)^k \quad (3)$$

3.1 Negligible parasitic reflections

In this section, we compare the properties of a parallel (or pile of plates) arrangement (see Fig. 2a) or a beam-displacement compensating arrangement (Fig. 2b, 2c) of two and four Si Brewster plates. The case of negligible parasitic reflection of the beam is considered here. This means the use of thick plates sufficiently separated between each other; thus, the parasitic reflections are spatially separated and do not overlap. Moreover, the proper treatment at the edges of the plate, such as grinding, is needed for mitigation of reflections at the edges.

When changing the wavelength of the p -polarized wave from 1.2 to 6.5 μm , the Brewster's angle changes from 74.2° to 73.7°, i.e. $\Delta\theta_B = 0.5^\circ$. Therefore, either the plates can be positioned under precise Brewster's angle for each wavelength, or a fixed mean value over the requested wavelength range. If two plates in the beam-displacement compensating arrangement are considered, the contrast $T_p : T_s$ can be calculated. As is shown in Fig. 4, for a precise value of the Brewster's angle, the contrast changes from 172 to 142 in the 1.2 – 6.5 μm transparency range. For the fixed mean value of the incidence angle at 73.9°, corresponding to the precise Brewster's angle for 1.85 μm , the contrast reaches a maximum value of 163, which is lower than values for the precise angle over a 1.2 – 1.85 μm part of the transparency range.

The precise Brewster's angle is higher than the fixed mean value here. Above $1.85 \mu\text{m}$ the contrast is higher for the fixed value of the incidence angle. The precise Brewster's angle is lower than the fixed mean value here. The decline is less steep in the whole transparency range for fixed value of the incidence angle. Which configuration works better in the considered wavelength range stems from the behavior of T_p' and T_s' around the Brewster's angle, see the inset of Fig. 3. While the T_p' has maximum at Brewster's angle and is changing very moderately in its vicinity, the T_s' decreases significantly and monotonically with increasing angle. I.e. if the set angle of incidence is higher than the actual precise Brewster's angle for given wavelength, the contrast is higher. In case of the four plates in the beam-displacement compensating arrangement and precise value of the Brewster's angle, the contrast changes from 2.9×10^4 to 1.9×10^4 . When the fixed angle is considered, the contrast varies between 2.6×10^4 and 2.1×10^4 . Being more convenient in practice, a fixed value of the Brewster's angle was chosen for subsequent testing of the two and four plate polarizers.

Fig. 4. Contrast dependence on wavelength for a fixed (73.9° , dashed curve) and precise (Brewster's, solid curve) angle of a two-plate (red curves) and four-plate (blue curves) polarizer, without consideration of parasitic reflections.

In the following text, only polarizers mounted under a fixed Brewster's angle for the whole transparency range are considered. If a 1 % loss in the transmittance of the p -polarization is acceptable, the sensitivity of the polarizer alignment can be studied in the range from $+3^\circ$ to -3° . The dependence of the contrast on angular detuning of both plates is depicted in Fig. 5. If angular detuning of a two-plate polarizer in a parallel arrangement is considered, the contrast can be actually improved up to ~ 300 by increasing the angle of incidence on both plates by $+3^\circ$. The asymmetry of the contrast between the positive and negative angular detuning stems from the behavior of T_p' and T_s' around the Brewster's angle as has been already discussed. When detuning the compensating arrangement, the change of angle of incidence on either plate is opposite. This results in a compensation of the change in the polarizer contrast and in this arrangement, the detuning of plates from 0° to -3° , $+3^\circ$ results in a contrast of over 145 over the whole transparency range (see Fig. 5). Moreover Fig. 6 shows that the p -polarized beam transmission remains above $\sim 98.8 \%$ for -3° , $+3^\circ$ detuning for both arrangements and is almost constant in the beam-displacement compensating arrangement case for the whole transparency range of silicon.

Fig. 5. a) Contrast dependence on wavelength for an angular detuning of a two-plate parallel silicon polarizer from $+3^\circ, +3^\circ$ (first plate, second plate) to $-3^\circ, -3^\circ$, without consideration of parasitic reflections. b) Contrast dependence on wavelength for an angular detuning of a two-plate beam-displacement compensating Si polarizer from $-3^\circ, +3^\circ$ (first plate, second plate) to $0^\circ, 0^\circ$, without consideration of parasitic reflections.

For the parallel arrangement and a misalignment by a certain angle both in the positive and negative direction, the curves representing the dependence of the T_p on wavelength intersect at a certain wavelength value. This value is moving towards shorter wavelengths with increasing misalignment angle. For positive misalignment, the dependence of the T_p on wavelength is decreasing and for the negative misalignment it is increasing. In the case of the beam-displacement compensating arrangement, the $T_p(\lambda)$ dependence is almost constant. To conclude, the contrast and transmission of the beam-displacement compensating arrangement is almost independent on perfect alignment.

Fig. 6. Dependence of the p -polarization transmission T_p on wavelength for an angular detuning of a two-plate parallel (solid curves) and beam-displacement compensating Si polarizer (dashed curve), where 0° corresponds to the fixed Brewster's angle of 73.9° . Legend of the figure: angle of the first plate, angle of the second plate, type of arrangement.

3.2 Non-negligible parasitic reflections

In the real-life case, parasitic reflections cannot be omitted. They are most significant in the case of more neighboring parallel plates or for thin plates, which can be represented by silicon wafers. If one plate of silicon is considered, the transmittance $T_{s-total}$ considering two silicon/air interfaces can be calculated from Eq. 4, where the first term refers to the beam, which is transmitted without any reflections on a silicon/air interface and the sum represents the contribution of the parasitic reflections, n being the number of parasitic reflections emerging from one plate. The parasitic reflections between the plates themselves are neglected here in order to avoid excessive complexity of the calculations. This assumption can be fulfilled by sufficient spacing between the plates. To calculate the total transmittance of the s -polarized component with a finite number of parasitic reflections, Eq. 5 can be used. As the number of parasitic reflections n approaches infinity, which represents the worst case scenario, the $T_{s-total}$ can be calculated from Eq. 6. To determine the contrast with an arbitrary number of parasitic reflections through a k -number plate polarizer, Eq. 7 can be used, which is in essence identical to Eq. 3, where T_p refers to the total coefficient for one plate. Note that possible interference effects between the parasitic reflections are not considered. The contrast dependence on the number n of s -polarized parasitic reflections in each plate is shown in Fig. 7.

$$T_{s-total} = T_s'^2 + T_s'^2 \sum_{i=1}^n R_s'^{2i} = \sum_{i=0}^n T_s'^2 R_s'^{2i} \quad (4)$$

$$T_{s-total} = T_s'^2 \frac{1 - R_s'^{2(n+1)}}{1 - R_s'^2} \quad (5)$$

$$T_{s-total} \xrightarrow{n \rightarrow \infty} \frac{T_s'^2}{1 - R_s'^2} \quad (6)$$

$$(T_p : T_s)_{k-plate}^{total} = \left(\frac{T_p}{T_{s-total}} \right)^k \quad (7)$$

Fig. 7. Calculated contrast dependence for multiple Si plates polarizers depending on the number of considered parasitic reflections n in each plate in Eq. 4. The lines are added to guide the eye.

As can be seen from Fig. 7, each added Si plate increases the contrast 12 times (i.e. ~ 10 dB) independently on the number of parasitic reflections in each plate. For the considered numbers of plates, the contrast converges to a constant value with increasing number of parasitic reflections. If one thin plate and an infinite number of parasitic reflections is considered, the contrast $T_p:T_s$ is approximately half of that without any parasitic reflections throughout the whole transparency region of silicon. For one plate and infinite sequence of parasitic reflections is considered, the contrast is 6. When an infinite sequence of parasitic reflections is considered in the s -polarization, the contrast for the two-plate and four-plate polarizer is 38 and 1426, which is approximately 4-times and 19-times less than that without any parasitic reflections, respectively.

Due to the parasitic reflection between the plates being neglected, the presented conclusions apply to both the parallel and beam-displacement compensating arrangements and their combinations. The beam-displacement compensating arrangement naturally eliminates the parasitic reflections between those plates, which are antiparallel. However, this arrangement is approximately twice as long as the parallel arrangement.

4. Attenuator system based on silicon Brewster plate-polarizer

Power attenuators of lasers outputs generally consist of a half-wave plate and a polarizer. In the mid-IR, there is a scarcity in broadband half-wave plates needed for such a setup and thus additional losses are introduced. A half-wave plate free attenuation setup is proposed here. If a linearly polarized beam is propagating through a silicon polarizer, which is being rotated, the output power is behaving according to the cosine squared dependence of the Malus' law. However, the plane of the output polarization is also being rotated. By adding another fixed Si polarizer at the output, the beam is polarized linearly accordingly to the orientation of the polarizer. The final dependence of the output power on the angle of rotation of the first polarizer is $I = I_0 \cos^2 \theta \cos^2 \varphi$, where θ is the angle between the input polarization and the rotating polarizer axis and φ is the angle between the polarization after the rotating polarizer and the axis of the fixed polarizer. If the fixed polarizer's orientation is parallel to the input polarization, the angles θ and φ are identical and the resulting intensity dependence is $I = I_0 \cos^4 \theta$.

5. Experimental verification of Brewster type Si polarizer performance

For initial testing of the Brewster type Si polarizer in the beam displacement compensating arrangement, a 1.55 μm , 50 mW continuous-wave Er-doped fiber laser was used. A long-pass filter (Thorlabs FEL1300) was used to filter out the residual pumping radiation at 980 nm. A Glan-Taylor polarizer and a polarizing beam-splitter cube were used for achieving a high degree of vertical polarization of the beam incident on the Si polarizer (Fig. 8). The uncoated and undoped Si plates of 75 mm $\times$ 20 mm aperture and 3 mm thickness were mounted into a single assembly. The assembly was attached to a tip, tilt, rotation mount to adjust the angle of incidence and the polarizing plane, respectively. The correct angle of the plates was ensured by a removable wedge, which was used for mounting of the Si plate holders on the base of the rotation mount. The assembly was aligned so that the beam went centered through the input and output aperture of the mount. The power at the Si polarizer output was measured by an Ophir 3A-P-V1 thermopile power meter. First, the two-plate arrangement was tested according to the experimental layout in Fig. 8, followed by testing of the four-plate polarizer (dashed line plates and beam path in Fig. 8). Note that the plane of polarization of the output beam was changing with the rotation of the Si polarizer.

Fig. 8. Experimental setup for two plate Si polarizer testing. In case of the four-plate polarizer testing, two more plates (dashed blue outlines) were added and the green dashed lines show the beam path. LPF - long pass filter FEL1300, GTP – Glan-Taylor polarizer, PBS – polarizing beam-splitter.

5.1 Contrast of the two-plate Si polarizer in a beam-displacement compensating arrangement

For the two-plate fixed incidence angle polarizer, the Malus' law (Fig. 9) and the contrast $T_p:T_s$ were measured. The Malus' law obeys a cosine squared dependence on the Si polarizer rotation angle. The measured contrast value was ~ 50 , which was approximately three times less when compared to the theoretical case when parasitic reflections are neglected. This shows the parasitic reflections of the s -polarized beam lowered the measured contrast and therefore cannot be neglected for the plates used. If an infinite sequence of parasitic reflections in the s -polarization is considered to be propagating through the two-plate polarizer, the calculated contrast is approximately 38. Because the output aperture of the real polarizer is limited, not all parasitic reflections reach the detector, which is why the actual measured contrast is higher than the one assuming infinite parasitic reflections. The contrast value of 50 corresponds to two parasitic reflections in each plate.

Fig. 9. Malus' law for a two-plate Brewster Si polarizer in the beam-displacement compensating arrangement. Minimum intensity level is affected by the parasitic reflections of the s -polarized beam.

5.2 Contrast of the four-plate Si polarizer in a beam-displacement compensating arrangement

In order to achieve a higher contrast, two more Si plates were added into the beam-displacement compensating setup. The contrast $T_p:T_s$ calculated without the consideration of parasitic reflections is then over 2.1×10^4 in the $1.2 - 6.5 \mu\text{m}$ range. If an infinite sequence of parasitic reflections of the s -polarized beam is considered propagating through the polarizer, the contrast is over 1.2×10^3 for the whole transparency range of Si. In the experimental results with the four-plate Si polarizer in a beam-displacement compensating arrangement (Fig. 10), the minimum value of power measured after the polarizer was at the $3 \mu\text{W}$ noise level of the detector. The error bars taking into account the $5 \mu\text{W}$ thermal drift and the 3 % accuracy of the detector are shown. If the noise level is taken as the lowest measurable value, the contrast would then be 1.8×10^4 .

Fig. 10. Malus' law measurements for a four-plate Brewster Si polarizer in beam-displacement compensating arrangement. Minimum intensity is at the noise level of the detector.

5.3 Contrast change due to the angular misalignment

We also studied the experimental dependence of the contrast on the angular detuning of the plates. The results can be found in Tab. 2. The contrast values for the parallel arrangement of the two plates are maximized for the detuning of $+3^\circ, +3^\circ$ and minimized for the $-2^\circ, -2^\circ$ case and correspond well with the calculated dependence (see Fig. 5), but the experimentally measured values of the contrast were lower than the calculated ones, due to the parasitic reflections. The same can be said about the beam-displacement compensating arrangement of the two plates with maximum measured contrast of 54 at the $-2^\circ, +2^\circ$ angular detuning. The trends of the measured contrast in dependence on angular misalignment are in agreement with the results presented in Fig. 5. For the four-plate polarizer, the minimum intensity values were at the noise-level of the detector for all angles of detuning.

Tab. 2 Experimental dependence of contrast on angular detuning of polarizer plates for two and four-plate parallel (A) and beam-displacement compensating (B) arrangement.

A) Parallel arrangement		
Angular detuning ($^\circ$)	Contrast $T_p:T_s$	
	Two plates	Four plates
$+3^\circ, +3^\circ$	116	
$+2^\circ, +2^\circ$	77	
$+1^\circ, +1^\circ$	66	Minimum intensity at noise level of the detector
$0^\circ, 0^\circ$	57	
$-1^\circ, -1^\circ$	50	
$-2^\circ, -2^\circ$	46	
$-3^\circ, -3^\circ$	Aperture too small	Aperture too small
B) Beam-displacement compensating arrangement		
Angular detuning ($^\circ$)	Contrast $T_p:T_s$	
	Two plates	Four plates
$+3^\circ, -3^\circ$	Aperture too small	Aperture too small
$+2^\circ, -2^\circ$	54	Minimum intensity at noise level of the detector
$+1^\circ, -1^\circ$	46	
$0^\circ, 0^\circ$	45	

^aIn the case of two plates, the angular detuning values indicate the incidence on the first plate and the second plate and in the case of the four-plate arrangement, these values indicate the angle of incidence on the first pair of plates and the second pair of plates, see Fig.8. The zero value indicates the fixed value of the Brewster's angle at 73.9° .

5.4 Observation of parasitic reflections

To understand how stacking more plates effectively eliminates parasitic reflections in the s -polarization, beam profiles of the transmitted s -waves were captured by the Spiricon Pyrocam III camera. To ensure high fidelity of the results, the output beam from a turn/key 1950 nm, continuous-wave Tm fiber laser system was preferred over the erbium fiber laser, because it provided several times more power. The power of the signal beam was set to 110 mW, which was sufficient for the observation of parasitic beams even after two Si plates. The setup was identical to that in Fig. 8, except for the radiation source and the detector, which was the Pyrocam III in this case.

As can be seen in Fig. 11a, after one plate placed under Brewster's angle, parasitic reflections of the s -polarization are present at the output of the polarizer. An addition of another Si plate placed in such a way, that the two Si-plates now form a beam-displacement compensating arrangement, an attenuation of the primary beam, as well as the parasitic reflections is visible in Fig. 11b. After adding one more parallel plate to the beam-displacement compensating arrangement, the beam is hardly visible on the Pyrocam (Fig. 11c) and after four silicon plates the s -polarized beam is no longer detectable by the Pyrocam. To conclude, the four-plate Si polarizer can be used to effectively attenuate an s -polarized beam and its parasitic reflections. In the p -polarization, no parasitic reflections are present after two or four Si plates (Fig. 12a and Fig. 12b, respectively).

Fig. 11. Fluence profiles of *s*-polarized beam after passage through a) one Si plate b) two Si plates (beam-displacement compensating arrangement) and c) three Si plates consisting of two plates in beam-displacement compensating arrangement and one additional parallel plate.

Fig. 12. Fluence profile of the *p*-polarized beam after the a) two-plate and b) four-plate beam-displacement compensating Si polarizer.

6. Separation of signal and idler beams of the broadband parametric mid-IR source

The proposed polarizer covers extremely large bandwidths. This ability can be used e.g. for the separation of perpendicularly polarized signal and idler beams at the output of type II, collinear optical parametric amplifiers. The transmitted beam is used and either of the two output beams can be selected by rotation of the polarizer by 90 degrees.

Here we discuss the use of the polarizer in the optical parametric amplifier system we have developed, which was described in more detail in the Introduction. The final optical parametric amplifier utilizes a KTA crystal, which is highly transparent up to the wavelength of $3.5 \mu\text{m}$ and therefore sets the upper limit on the wavelength in our considerations. The output signal and idler beams cover the range between $1.4 \mu\text{m}$ and $3.5 \mu\text{m}$. Due to the principle of optical parametric amplification, the ratio of intensities of the signal and idler beams $I_{\text{signal}}/I_{\text{idler}}$ is proportional to the ratio of their respective wavelengths $\lambda_{\text{idler}}/\lambda_{\text{signal}}$, according to Eq. 2.14 in [26]. The intensity of the idler beam, which has longer wavelength, is thus lower compared to the signal beam intensity and the contrast of the polarizer is therefore more critical if the idler beam is the primary transmitted beam, i.e. the idler beam is *p*-polarized.

We require the intensity ratio of the signal to the idler beam transmitted through the polarizer to be less than 1 % for the case of a *p*-polarized idler beam. For the two-plate Si polarizer and without considering the parasitic reflections, the requirement on separation could be easily achieved when the signal beam is the *p*-wave. Because the signal beam is more powerful than idler beam, contrast will be always better than $T_p:T_s \sim 147$, which is a value for two equally powerful beams. However, in the case of the idler being the *p*-wave, the

requirement of 1 % signal to idler ratio for the p polarized idler is met only until reaching 2.55 μm of the idler wavelength, where $\lambda_{\text{idler}}/\lambda_{\text{signal}}$ equals 1.47. Then the ratio of the intensities increases up to 1.6 % at 3.5 μm idler wavelength. When the parasitic reflections are considered, the ratio worsens and can increase up to 6.8 % at 3.5 μm idler wavelength. The two-plate polarizer therefore does not meet the strict requirement for the separation of the output beams. For the four-plate Si Brewster polarizer, without consideration of the parasitic reflections, the ratio of the signal and idler intensities is lower than approximately 0.005 % over the 1.4 – 3.5 μm wavelength range for both signal and idler being the p -wave. When parasitic reflections are considered and idler is the p -wave, the ratio of the signal and idler intensities is 0.19 % and in the case of signal being the p -wave, the ratio of the intensities is 0.03 %. The four-plate polarizer outperforms the requirements on separation by one order of magnitude, even when an infinite sequence of propagating parasitic beams in the s -polarization is considered.

The signal and idler beam separation was tested experimentally. The two-plate Si polarizer in the beam-displacement compensating arrangement was tested for the signal wavelength of 1800 nm and the corresponding idler wavelength of 2400 nm. The signal and idler beam sum power was first measured without the polarizer, i.e. without any separation of these beams. Subsequently, the polarizer was added. The polarizer was rotated by 90°, so that either signal or idler beam would be p -polarized. The powers transmitted for both positions of the polarizer were measured separately and then summed. Values of the signal and idler sum powers acquired by these two methods are presented in Fig. 13. As this figure shows, the sum value acquired by first separating the two beams and summing their measured powers manually is larger than that measured without any separation. This means that the two-plate polarizer is unable to provide sufficient contrast, due to s -polarization leakage through the device. The difference between the two powers varies between 10 and 20 %. The difference is expected to increase with the increasing gap between the signal and idler wavelengths due to increasing ratio $I_{\text{signal}}/I_{\text{idler}}$. The variation in difference between the two powers caused by the leaked s -polarization is explained by the error bars, which take into account the contribution of the measured power fluctuations and power meter accuracy.

Fig. 13. Comparison of the sum powers of signal ($\lambda = 1800$ nm) and idler ($\lambda = 2400$ nm) beams generated by the mid-IR source measured with and without separation by a two-plate beam-displacement compensating arrangement.

On the other hand, when the four-plate beam-displacement compensating Si polarizer is used, the two measured values of the sum powers correspond well in the wavelength range 1700 – 2600 nm (Fig. 14). Therefore, the four-plate beam-displacement compensating arrangement of the silicon Brewster plate polarizer is a suitable tool for signal and idler beam separation of a broadband, high-power mid-IR optical parametric source.

Fig. 14. Comparison of the sum powers of signal ($\lambda = 1700$ nm, 1950 nm) and idler ($\lambda = 2600$ nm, 2180 nm) beams generated by the mid-IR source measured with and without separation by a four-plate beam-displacement compensating arrangement.

7. Conclusion

As a response to the scarcity of broadband mid-infrared polarizers and wavelength separators, we have developed a transmission-type Brewster polarizer consisting of two or four silicon plates in a beam-displacement compensating arrangement. In the case of thick plates, which reduces the parasitic reflections, the calculated contrasts of the two-plate and four-plate polarizers are ~ 160 and $\sim 2.6 \times 10^4$, respectively. In the case of thin plates, where the parasitic reflections cannot be neglected, the contrast in the two-plate polarizer reduces approximately to the value of ~ 38 , while for the four-plate polarizer, the infinite sequence of parasitic reflections introduces a decrease to ~ 1425 in polarizer contrast.

The theoretical predictions were confirmed experimentally. During experimental testing of the Si polarizer with two thin plates, parasitic reflections in the *s*-polarization were found to lower the measured contrast by almost two-thirds. The four-plate polarizer was found to attenuate the *s*-polarization with sufficient contrast. Moreover, the four-plate polarizer effectively separated the signal and idler beams of the broadband mid-infrared parametric source in the $1700 - 2600$ nm wavelength range.

Overall, the assembly of four silicon plates under Brewster's angle is suitable for use in polarizers, attenuators, and separators of high-power signal and idler beams of optical parametric amplifiers or oscillators utilizing the type II interaction, where the signal and idler beams have perpendicular polarizations. It can be used over the whole high transparency range of silicon, ranging from 1.2 to ~ 6.5 μm . Moreover, the proposed separation enables gap free tuning.

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Disclosures

The authors declare no conflicts of interest.

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