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Infrared broadband 50%-50% beam splitters for s-polarized light

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Prisms and slabs made of high-refractive-index materials such as ZnSe, Ge, and Si can be designed as broadband, 50%–50%, beam splitters (BSs) for obliquely incident *s*-polarized light in the near- and mid-IR. The beam-splitting face of the prism or slab is uncoated, while the exit face is antireflection coated. The split beams travel in orthogonal directions when light is incident at the Brewster angle. A novel design is also described that uses Brewster-angle reflection at the SiO_2–Si interface to achieve a 50%–50% *s*-polarization BS over the 1.2–3.5 μm spectral range. Such *s*-polarization BSs are particularly suited for interferometry and holography.

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1. Introduction

In interferometry,[1] off-axis holography,[2] and the recording of fiber-Bragg gratings,[3] and phase masks,[4] two waves traveling in different directions are superimposed. To attain maximum fringe visibility in the interference pattern, the two waves should be identically polarized. This is achieved most readily if the two waves are *s* polarized, with the electric field vector of both waves oscillating in a common direction perpendicular to the interferometer plane. The *s*-linear polarization also happens to be the eigenpolarization[5] of higher reflectance of the steering mirrors that are often used to deliver the two beams to the recording plane. In contrast, the orthogonal *p* polarization, with the electric field oscillating in the plane of the interferometer, is not suitable when the two beams intersect at a large ($>15°$) angle.

In this paper, prism and slab beam splitters (BSs) for *s*-polarized light are considered that use high-refractive-index substrates in the IR. The BSs are designed to achieve: (i) reflected and transmitted beams of equal power (50%–50% split), (ii) two split waves that travel in orthogonal directions (which is desirable in the classical Michelson and Mach–Zehnder interferometers[1]), and (iii) broadband operation in the near and mid-IR.

Section 2 reviews the basic geometrical optics of light reflection and transmission by a prism or a slab of dielectric material. In Section 3, a Brewster angle, ZnSe prism, 50% BS for *s*-polarized light in the mid-IR is proposed. In Section 4, Ge- and Si-slab *s*-polarization BSs are presented that are oriented at angles other than the Brewster angle. In Section 5, a novel broadband, near-IR BS for *s*-polarized light is described, which uses reflection at the Brewster angle by an embedded interface between optically contacted SiO_2 (fused silica) and Si prisms. Finally, Section 6 gives a brief summary of the paper.

2. Geometric Considerations

Figure 1 shows cross sections of the prism and slab beam splitters for *s*-polarized light. In Fig. 1(a), a collimated beam of monochromatic light is incident from air at an angle φ on the hypotenuse face of a right-angle prism, which is uncoated. The prism angle α is chosen equal to the angle of refraction,

$$\alpha = \arcsin[(\sin \varphi)/n], \tag{1}$$

according to Snell's law. This ensures that the refracted beam leaves the prism normal to its exit face, which is antireflection coated (ARC). In Eq. (1), n is the refractive index of the prism. The angular separation β between the reflected and the transmitted beams is given by

$$\beta = 180° - (\alpha + \varphi). \tag{2}$$

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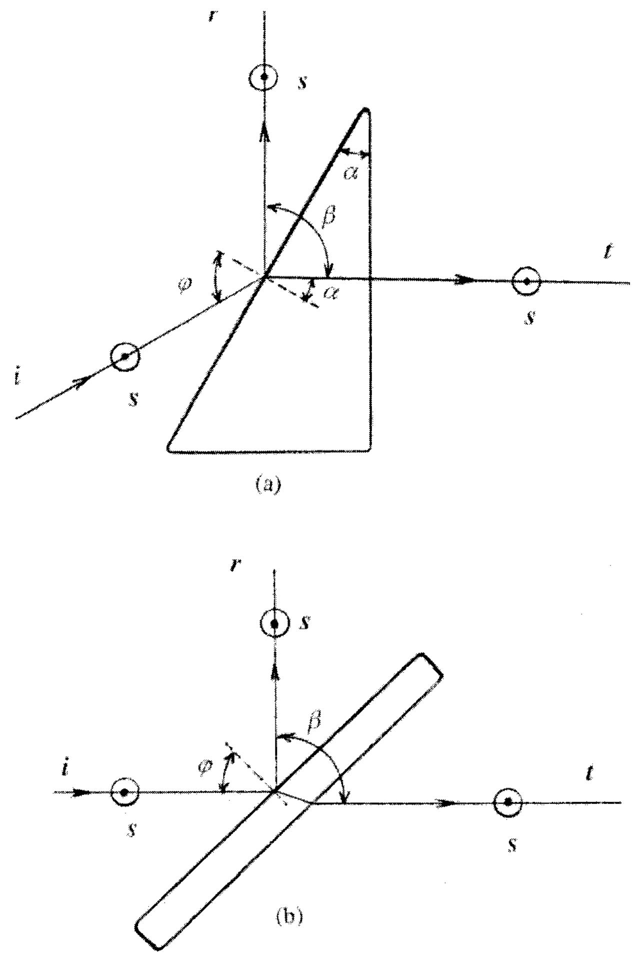

Fig. 1. Cross sections of the (a) prism and (b) slab beam splitters for s-polarized light.

The reflected and transmitted beams travel in orthogonal directions when

$$\beta = 90° = (\alpha + \varphi). \tag{3}$$

This occurs when φ is the Brewster angle[5] for light reflection at the ambient–substrate interface,

$$\varphi = \varphi_B = \arctan(n). \tag{4}$$

In Fig. 1(b), the uniform-thickness slab BS produces a transmitted beam that is parallel to the incident beam but is laterally displaced by a distance that is proportional to the slab thickness, and is also a function of n and φ. The exit face is ARC for the s polarization at oblique incidence. For this parallel-slab BS, the angular separation is simply given by

$$\beta = 180° - 2\varphi, \tag{5}$$

and the split beams are orthogonal only if $\varphi = 45°$.

3. Brewster-Angle Prism Beam Splitter for *s*-Polarized Light

To achieve an intensity reflectance $R_s = 0.50$, the corresponding amplitude reflectance for s-polarized light is

$$r_s = -R_s^{1/2} = -1/\sqrt{2}, \tag{6}$$

where the minus sign is consistent with the Nebraska–Muller conventions.[6] At the Brewster angle, $r_p = 0$, and we also have[7]

$$r_s = \cos(2\varphi_B). \tag{7}$$

From Eqs. (6) and (7), it follows that

$$\varphi_B = 67.5°, \tag{8}$$

hence the prism angle α is

$$\alpha = 90° - \varphi_B = 22.5°. \tag{9}$$

And from Brewster's law,[5] the prism refractive index is

$$n = \tan \varphi_B = \tan 67.5° = \left(1 + \sqrt{2}\right) = 2.4142. \tag{10}$$

The refractive index of a quarter-wave, single-layer ARC on the exit face of the prism is given by[8]

$$n_f = \left(1 + \sqrt{2}\right)^{1/2} = 1.5538. \tag{11}$$

An IR-transparent material with a refractive index very close to 2.4142 [Eq. (10)] is ZnSe, or Irtran 4. The latter is a hot-pressed polycrystalline form of ZnSe made by Kodak. We have found that the refractive index of ZnSe in the 8–11 μm spectral range[9] can be fitted by a simple linear dispersion relation:

$$n = 2.466 - 0.006\lambda, \tag{12}$$

where λ is the wavelength in μm, and the error in n is of the order of 0.001 or less. According to Eq. (12), $n = 2.418$ at $\lambda = 8$ μm, $n = 2.400$ at $\lambda = 11$ μm, and the special value $n = (1 + \sqrt{2}) = 2.4142$ is attained at $\lambda = 8.633$ μm. By controlling the parameters of the process (e.g., pressure) by which Irtran 4 is made, the refractive index may be tuned to $n = 2.4142$ at selected laser wavelengths to suit specific applications.

The intensity reflectance, $R_s = r_s^2$, is calculated from the Fresnel amplitude reflection coefficient for s polarization,[5]

$$r_s = \frac{\cos \varphi - \left(n^2 - \sin^2 \varphi\right)^{1/2}}{\cos \varphi + \left(n^2 - \sin^2 \varphi\right)^{1/2}}, \tag{13}$$

as a function of the angle of incidence φ and substrate refractive index n. For example, for a ZnSe substrate,

$n = (1 + \sqrt{2}) = 2.4142$ at $\lambda = 8.633$ μm, and with $\varphi = \varphi_B = 67.5°$, we obtain $R_s = 0.50$, as expected. If the angle of incidence is unchanged, but the wavelength is shifted to $\lambda = 11$ μm, n drops to 2.400 and $R_s = 0.4976$. The corresponding change in the angle of refraction is only 0.34°. The small changes in the s reflectance and direction of refraction confirm that the BS performs well over the 8–11 μm spectral range. It is assumed that the ARC on the exit face of the prism performs at least equally well (reflectance <0.5%) over the same bandwidth.

The lack of high-refractive-index materials in the visible spectrum makes it difficult to implement the s-polarization prism BS in this spectral range. An exception is diamond,[10] which has the requisite refractive index of $n = (1 + \sqrt{2}) = 2.4142$ at $\lambda = 614.35$ nm. However, bulk diamond is expensive, which makes this proposition impractical.

4. Parallel-Slab Beam Splitter for *s*-Polarized Light

A plane-parallel dielectric slab of high-refractive-index n, Fig. 1(b), which is tilted at a suitable angle of incidence φ, offers a simpler design for an s-polarized light BS. If we start from Eq. (13), the constraint on n and φ, such that the intensity reflectance for s-polarized light is 50%, can be put in the convenient form

$$n^2 = 1 + (16 + 12\sqrt{2})\cos^2\varphi. \tag{14}$$

For example, at the desirable angle $\varphi = 45°$, Eq. (14) gives the required refractive index as

$$n = (9 + 6\sqrt{2})^{1/2} = 4.182. \tag{15}$$

Fortuitously, this is the refractive index of Ge at the short-wavelength end of its transmission range,[11] approximately 2 μm in the near IR.

A Ge slab can be used as an s-polarization BS over a broad mid-IR spectral range (6 to 18 μm), where its refractive index is nearly constant[11] at 4.0. To achieve $R_s = 0.50$, the slab must be tilted at an angle of incidence >45°. Such an angle is obtained by substituting $n = 4.0$ in Eq. (14); this gives

$$\varphi = 47.585°. \tag{16}$$

On the other hand, if a Ge slab of refractive index 4.0 is set at the convenient angle $\varphi = 45°$ (so that the beams reflected and transmitted by the slab are orthogonal), we obtain $R_s = 48.37\%$, which differs from the target value of 50% by <2%. If necessary, the refracted beam can be attenuated slightly by an imperfect ARC on the exit face of the slab so that the reflected and transmitted beams have equal power (48.37% each).

Another suitable material for the slab BS is Si, which has a refractive index of nearly $n = 3.4$ over a broad (4–11 μm) spectral range.[12] Use of this index in Eq. (14) yields

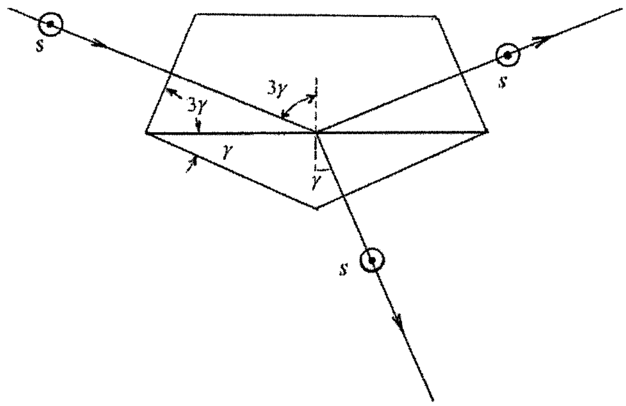

Fig. 2. Biprism BS for s-polarized light consists of a top prism of SiO_2, which is optically contacted to a bottom prism of Si. The angle γ is 22.5° and all other angles are integral multiples of γ. The angle of incidence of s-polarized light at the SiO_2–Si interface is 67.5°.

$$\varphi = 55.533°, \tag{17}$$

as the required tilt angle of the Si slab to function as a 50%–50% BS for incident s-polarized light.

The exit face of the Ge or Si slab should be ARC for the s polarization at oblique incidence, e.g., using techniques that are described elsewhere.[13,14]

5. Broadband Near-IR Biprism Beam Splitter for *s*-Polarized Light Using Reflection at the SiO_2–Si Interface

Figure 2 shows a novel biprism BS that consists of a top prism of SiO_2 (fused silica) that is optically contacted to a bottom prism of Si. The angle γ is 22.5° and all other angles are integral multiples of γ. Light, which is s polarized, is incident on the SiO_2–Si interface at 67.5°. From the known dispersion of SiO_2 and Si,[10] the relative refractive index of the SiO_2–Si interface,

$$n = n(\text{Si})/n(\text{SiO}_2), \tag{18}$$

is calculated and plotted as a function of wavelength[15] λ in Fig. 3. From Fig. 3, we see that the condition

$$n(\lambda) = (1 + \sqrt{2}) = 2.4142 \tag{19}$$

is satisfied at two wavelengths,

$$\lambda_1 = 1.4224\ \mu\text{m}, \quad \lambda_2 = 2.8644\ \mu\text{m}, \tag{20}$$

and n remains close to 2.4142 in the 1.2–3.5 μm spectral range. Therefore the angle 67.5° is, or very near to, the Brewster angle of light reflection at the SiO_2–Si interface, and the biprism shown in Fig. 2 functions as a 50%–50% BS for s-polarized light over a significant bandwidth in the near IR. Furthermore, reflection at the Brewster angle splits the incident light beam into two beams that travel in orthogonal directions.

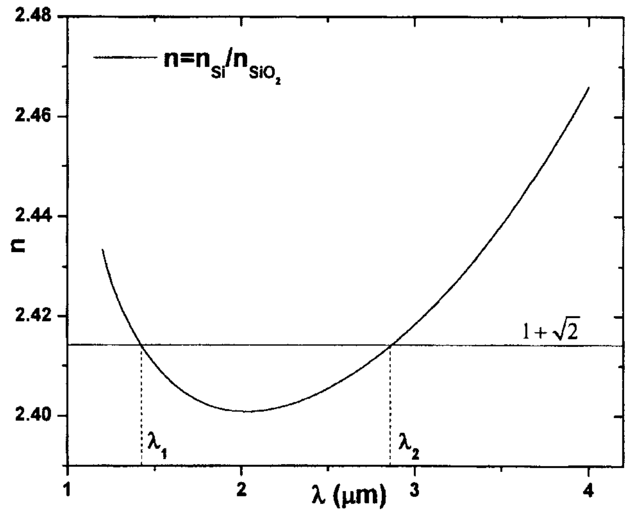

Fig. 3. Relative refractive index of the SiO_2–Si interface, Eq. (18), is plotted as a function of wavelength in λ μm. Note that $n(\lambda) = (1 + \sqrt{2}) = 2.4142$ at two wavelengths $\lambda_1 = 1.4224$ μm and $\lambda_2 = 2.8644$ μm (after Ref. 15).

Total internal reflection at the Si–SiO_2 interface at an angle of incidence near 33° was shown previously to provide achromatic broadband quarter-wave retardation.[15] Other Si-based reflection retarders and polarizers have also been described.[16]

6. Summary

Broadband, 50%–50%, near- and mid-IR beam splitters for *s*-polarized light can be readily designed using high-index prism and slab substrates, such as ZnSe, Ge, and Si. The split beams travel in orthogonal directions when light is incident at the Brewster angle. A novel design that uses Brewster-angle reflection by a SiO_2–Si biprism as an *s*-polarization beam splitter over the 1.2–3.5 μm spectral range has also been proposed. These *s*-polarization beam splitters are particularly suited for interferometry and holography.

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