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Competitive light beam splitters based on complex interference wedged structures that use low-reflectivity components (Fresnel reflection)

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Abstract. We demonstrate that interference wedge structures suitably composed of wedged purely glass elements using Fresnel reflection only can be effectively employed for realization of competitive light beam splitters and filters (especially for high-power laser beams). The theoretical analysis, simulation and experimental testing show that for appropriately chosen parameters and for a suitably composed interference complex such structures can achieve a controlled variable transmission in a wide range (99% – ~30%) and reflection from ~2% to ~70%. The traditional realization of purely glass splitters ensures no more than ~20% reflectivity. The splitters proposed are very compact sheet-like elements (e.g., 5×3×0.2 cm) and the splitting is implemented by sliding in the splitter's plane. Thus, the propagation direction of the formed beams is preserved. The incident beam on the purely glass splitter (no dielectric or metallic mirrors) can be of high power and the influence of the air humidity is strongly reduced; also, cleaning the filter surfaces presents no difficulties. A single splitter can work in a wide range of wavelengths (IR, visible) without polarization dependence for incident angles up to ~20^{o}.

1. Introduction

The interference wedged structures (IWS) [1-3] are a type of interference structure that is not very popular, having mainly applications as spectral analyzing elements and in surface flatness control. In our previous works, we have shown an interesting and useful new possibility for their applications in laser technology as elements for laser spectral control: two-wavelength lasers, continuously tunable single-mode lasers, including devices using the new basic properties found and developed by us of the discussed structures – non-Snell's spectral selective reflection and non-symmetry in transmission [4]. Recently, as a new development, we have introduced new structures of this type – composed tunable interference wedged structure (CTIWS) that ensure the spectral selection of narrow line (e.g ~ 0.01 nm) in combination with the large tuning range of more than 10 – 50 nm) [5]. We have shown the potential of their application by implementing novel wavelength division multiplexing elements for optical communications systems that select the desired wavelength with controlled power from a multi-wavelength beam. Their essential properties are the linear tuning of the wavelength of the selected resonance by sliding the structure in its plane along the arms of the composed wedges.

Another interesting potential application of the IWS is to use them with suitable parameters and compositions as competitive light-beam splitters – interference wedge beam splitters (IWBS), discussed in detail in [6, 7]. Such usage is based on the transmission variation around the position of the resonance line. This property allows one to preserve the direction of propagation of the beam during sliding. The actual implementation of these potential applications requires finding the appropriate composition and parameters. In the works referenced above, we have improved the characteristics of the standard traditional IWS by choosing a suitable combination of dielectric wedged layers and dielectric mirrors.

In the present paper, we report on the development by theoretical consideration and experimental testing of a type of IWBS based on CIWS that allow one to realize competitive and practically applicable IWBS using only wedged glass plates with Fresnel reflection. The use of a purely glass design rather than dielectric layers and dielectric or metallic mirrors leads to significant advantages for practical applications.

In general, when discussing optical beam splitters (including their use as filters), one should bear in mind that such elements are widely employed in many scientific and R&D optical laboratories, in medical laboratories and in industrial entities, so that their further development is of pressing interest.

2. Short presentation of the IW and the CIWS as the basis of the beam splitters developed

The splitters developed in the work are based on interference wedged structures (IWS) in their simple realization, namely, the interference wedge (IW), or a suitable combination of such wedges – composed interference wedged structure (CIWS). The IW is a single transparent wedged layer (wedge 'gap') with reflective sides (multi-dielectric mirrors), as schematically shown in figure 1 (a).The corresponding notations are: R_1 and R_2 for the reflective sides ($R_{1,2}$ denote also the reflectivity); n_i and n_0 are the refractive indexes of the layer and of the environment; α is the wedge apex angle of the gap, e_i is the geometrical and $e_i^* = e_i . n_i$, the optical thickness of the gaps in place i; θ is the incident angle of the laser beam IB with respect to the IWS front mirror.

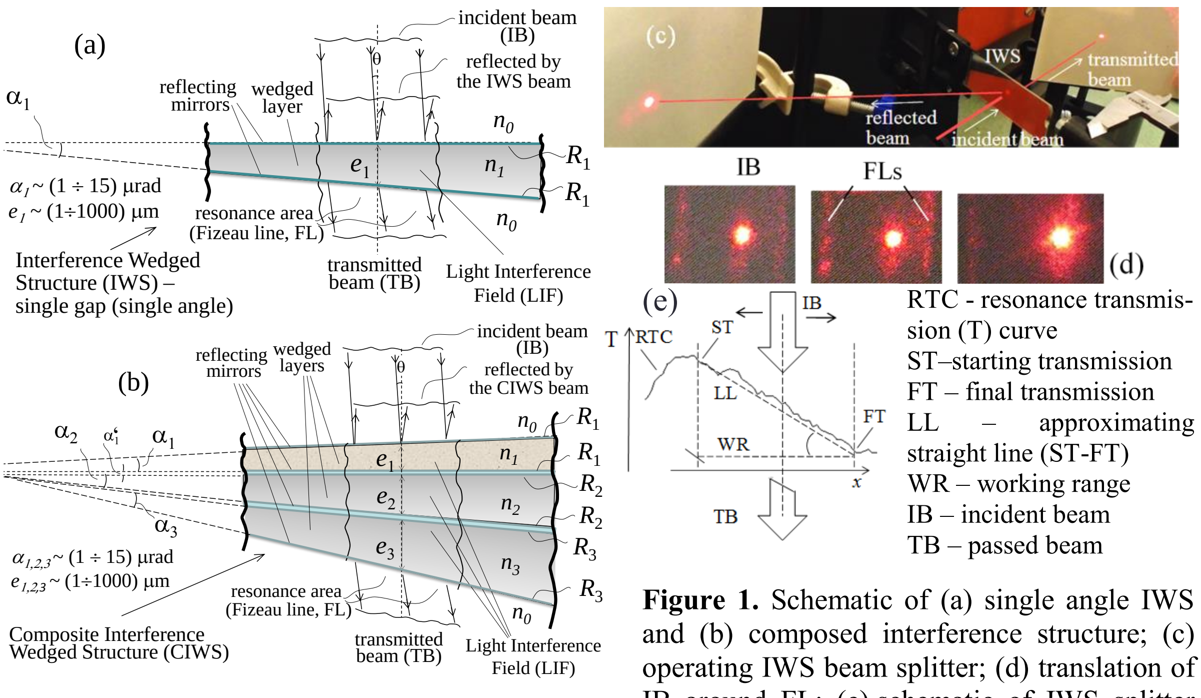

Figure 1. Schematic of (a) single angle IWS and (b) composed interference structure; (c) operating IWS beam splitter; (d) translation of IB around FL; (e) schematic of IWS splitter action with notations.

The well-known general theory of a single-gap IWS (i.e. an IW) [1, 2] states that when an IW is illuminated by a collimated large-size monochromatic beam (a laser beam) with a wavelength λ_i, the passing light forms along the arm of the wedge angle α a sequence of parallel transmission lines –

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figure 1 (c). The places of this resonance lines (or Fizeau lines) with maximum transmission are equally spaced by $\Delta x = (\lambda_i/2n)\tan\alpha$ and at thicknesses $e_r.n = k(\lambda_i/2n)$, where k is an integer.

Of general interest are the physical parameters that are shown in the figure: linearly decreasing transmission T (and linearly increasing reflectivity R) with the linear variation of the splitting ratio; the splitter operates well with a high difference between the starting transmissions (maximum) ST in % and the final (minimum) FT in %. An essential parameter is the working range (WR, in mm) that is the length of the projection of the line LL (line ST-FT) on the axis of translation. Another characteristic is the slope of the line LL (ST-FT/WR in %/mm). A high WR and a low slope ensure good splitting because of the smooth control and the small deformation of the beam by the transmission difference between the WR ends. Of practical interest are the possible incident power that does not lead to damage, the resistance to adverse ambient conditions, especially humidity, and the possibility for easy cleaning.

The IWBS discussed in the work are based on the properties of composed interference wedged structures (CIWS), which are built as a combination of glass and air-gaps interference wedges with suitable parameters and can act as competitive light beam splitters using only Fresnel reflection of the glass plates (no mirrors and dielectric layers). Figure 2 shows a schematic of such a variant of CIWS (multi-angle interference wedged structure) as a complex of two single wedged glasses and an air wedge.

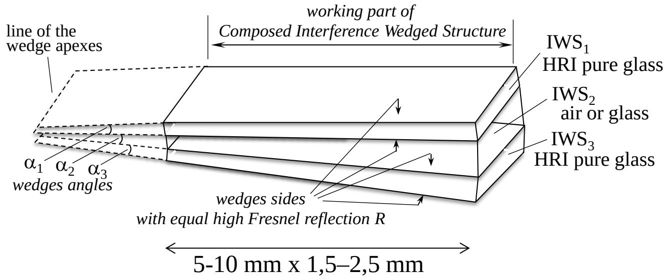


Figure 2. Schematic of variant of CIWS constructed only by two pure glass wedged plates and air-gap wedge. All composed wedges use only Fresnel reflection. The parameters are given in the text.

3. Analytical approach

The precise theoretical treatment of IWS is complicated, especially concerning the CIWS as a combination of such structures. We have developed a simplified approach to describing mathematically the operation of the IWS [6]. The basic idea is to consider the IW as consisting of a sequence of Fabry-Perot interferometers (FPI) with linearly increasing (or decreasing) thicknesses located next to one another along a line perpendicular to the wedge apex. The approach combines the expression for the transmission T (equation (1)) of Fabry-Perot interferometers [1] with an expression (added by us) for the linear variation of the thickness $e(x)$ of the IW (equation (2)):

$$T = (1-R)^{2}/(1-2R.cos\delta + R^2) \tag{1}$$

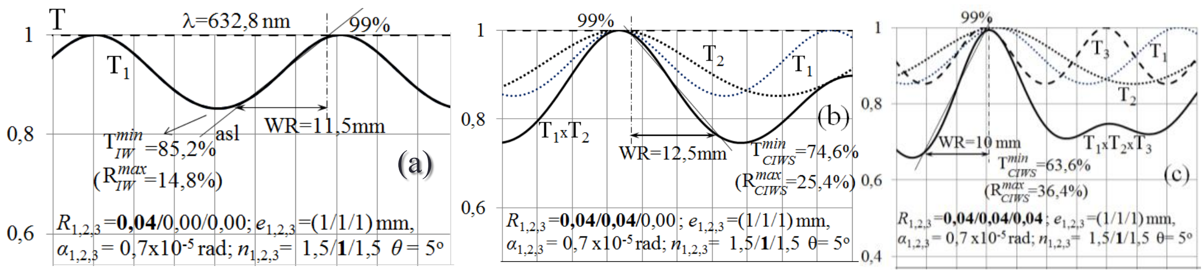
with $\delta = (2\pi/\lambda).2.e.n.cos\theta$. In what concerns the parasitic losses, for losses up to ~3% a computer analysis ignoring the losses yields results acceptably close to both the ideal case without losses and to the results obtained experimentally. From the thickness variation of the IWS we have $e\,(p) = e_0 + x.\tan\alpha$, where x is the distance from the starting thickness e_0, or the thickness of a chosen resonance. Thus, in (1) we substitute for δ:

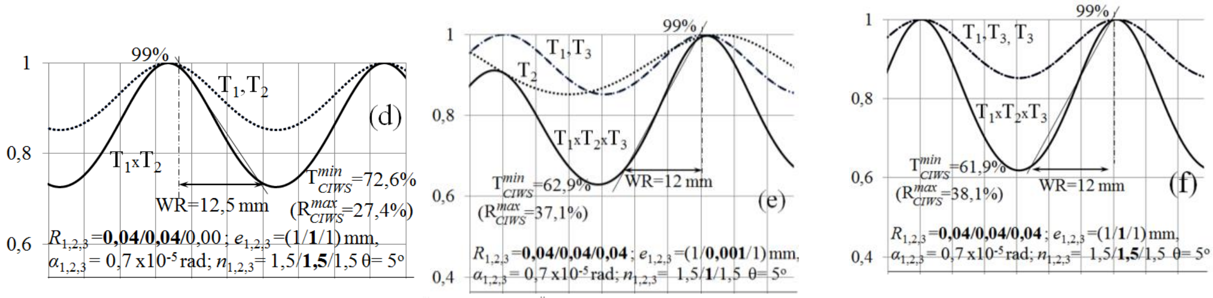
$$\delta(x) = (2\pi/\lambda).2.(e_0 + x.\tan\alpha).n.cos\,\theta \tag{2}$$

Combining (1) with (2) we can calculate for given e_0 the corresponding resonance transmission curve as a function of e_o, λ, p, θ, α, n and R. We consider two cases of real commercial optical glasses – a standard glass with a refractive index of 1.5 ensuring a reflectivity $R = 0.04$ used in the experimental testing, and a special heavy glass with a refractive index of 2 ($\approx$ 2) and reflectivity $R \approx 0.11$. We verified the results of the approach presented taking into account the low reflectivity of the side of the used sub-structure ($R \sim 0.04 - 0.11$). This allows one to obtain the interference pattern by modelling the multi-reflection of the rays propagating inside the structure, followed by summing the amplitudes of the formed waves. The low reflection noted permits one to limit the consideration to three sequential reflections and the formation of three secondary waves by this reflection. The amplitudes of the waves after three reflections are practically 0 without any impact on the results. The results are comparable with the results given by (1) and (2).

4. Modeling and computer simulation

The properties of complex interference wedged structures made of purely glass components are considerably better than those of the same type of single-angle splitters. Our aim is achieving variable and controlled splitting. We start the analysis with the case of wedged glass plates with $n = 1.5$ (Fresnel reflection $R = 0.04$) of the glass-air sides of the plates and compare the results with those of using glass with a refractive index of $n \approx 2$ and $R \approx 011$. Such glasses are offered in the specialized optical market. Let the single angle interference wedged structure (i.e., IW) have typical parameters of $\alpha \sim 0.7{\times}10^{-5}$ rad and $e_0 \sim 1000$ µm (hard single glass component). The laser beam wavelengths considered are $\lambda = 632.8$ nm (red He-Ne laser), 1.064 – 1.33 nm (Nd-YAG); 0.7 – 0.8 nm (green–yellow). The incident beam angles with respect to the splitter surface are ~ 5 – 12^0 (typically ~5^0), which excludes polarization dependence and is a scheme accessible for practical applications. The beam diameters are of the order of 1 – 2 mm; for wider beams, as we have shown, the beam can be split after focusing. The computer graphs obtained for the discussed IW parameters bearing in mind the discussion in Section 2 are plotted below in figure 3, where 3 (a) is a graph of the transmission T of the simple splitter IW – a wedged glass plate; the graphs in figure 3 (b)-(h) are representative of more complex multi-angle structures. The parameters of each composed structure IW_1, IW_2, IW_3 that build the complex CIWS are given in the corresponding notations under the graphs numbered accordingly. R equal to 0 denotes the absence of the respective structure. As can be seen, using a suitable combination of wedged structures – glass gap, air gap, angles and thicknesses, we can obtain useful splitting parameters with the transmission T varying from 99% to 28% and a maximal R from 0 to ~70%. Note that the CIWS composed by two wedged glass plates in close contact exhibits at a suitably chosen place (line) a behaviour comparable to the three wedged structures of glass wedge – air wedge – glass wedge. Thus, between the glasses there exists a very thin, of ~ µm, air wedge (graphs 3d, 3e). Generally, an absolutely close contact existing between two glasses of the same type can eliminate the reflection from the contact surfaces, which is not the case for non-ideal surfaces. From a practical viewpoint, this permits one to compose a well working splitter by superposition of two or three suitably chosen wedged glass plates.





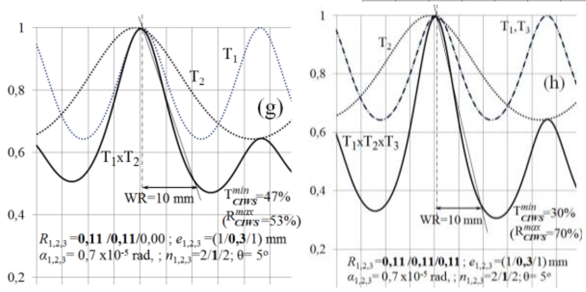


Figure 3. Computer graphs for: (a) – transmission T of simple splitter IW – a wedged glass plate; (b)-(h) transmission of complex multi-angle structures. The parameters of the structures are given in the corresponding graphs.

5. Experiment

We used pure glass (n = 1.5; R = 0.04) IW elements (single-gap IWBS) with a thickness of 1 mm and a wedge angle of 0.7×10^{-5} rad. The transmission and reflection measured correspond very well to the calculated ones given in figure 3 (a) and illustrated in figure 4 (a)-(c), where (here and below) the illumination was by a 632.8-nm He-Ne laser beam that after the aluminium mirror (R ~ 75%) had a power of 9 mW with 1-mm beam diameter and an incident angle of 5°.

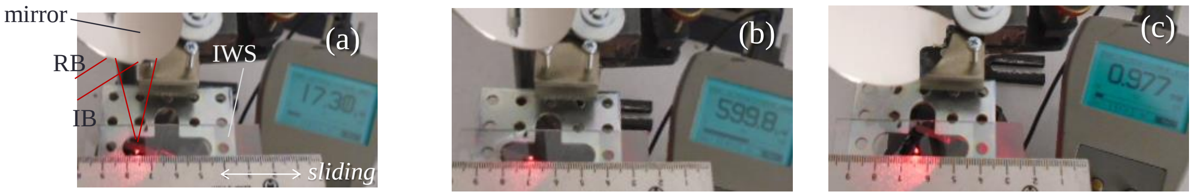


Figure 4. Selected pictures of measurement of the transmission and reflection of single-gap IWBS, which is constructed as single-glass element (for the parameters – see the text).

The point of incidence of the beam was varied by sliding the IW. The readings on the power meter display (Thorlabs PM10) are also shown. The reflection R of the IWBS varying from ~ 0.1 to 1.25 mW (i.e. ~1% to 14%, accounting for the losses of 25% in the mirror) can be seen for the three positions of the IWBS. Figure 5 (a) illustrates the reflection of the structure of two superimposed wedges (CIWBS) varying from 0.1 mW to 2.9 mW (~1% to 32%); and for the three-wedge CIWBS, from 0.50 mw to 4.2 mW (6% to 44%), also acceptably close to the calculated values in figure 3 (c). We also focused the incident beam and found that the splitter works well with a focal spot diameter of ~ 0.2 mm).

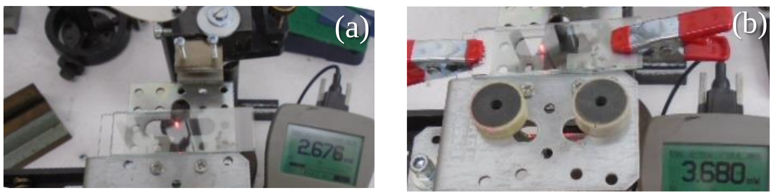


Figure 5. Two (a) and three (b) glass wedges composed IWBS.

6. Conclusion

The results of the experimental test is in good agreement with the theoretical estimates and confirm the possibility of implementing purely glass splitters and filters based on Fresnel reflection that provide splitting in transmission from ~99% to 27% and in reflection, from ~0 to ~73 % (the last results based on using heavy glass with $n = 2$ and $R = 0.11$). The small discrepancy between the calculated and the experimentally measured results (e.g. 32% instead of 28%) may be related to the inaccurate knowledge of all parameters of the glasses and wedges; however, the results demonstrate well the potential of the splitters developed.

Acknowledgements

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