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Utilization of Pure Glass Composite Interference Wedged Structures as Highly Efficient Light Beam Splitters

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Abstract – **We present a developed approach for analysis and optimization of new, pure glass light beam splitters as instrumentation, especially for high intensity laser beam splitting. The method is based on our previously introduced Composed Interference Wedged Structures. The linear division from 100% to 10% is performed via sliding a plate splitter in a range of 50 mm. Among the advantages of the method are no change of direction of the formed beams, no polarization requirements, low losses, maintenance.**

Keywords – **pure glass, interference wedged structure, high efficiency, light beam splitter**

I. INTRODUCTION

In the series of our proposals and investigations related to Interference Wedged Structures (IWSs) and their applications in laser technologies [1-3], we present the optimization and potential of proposed by us principle of new instrumentation for optical and laser applications. Based on a novel structure we introduced, the Composite Interference Wedged Structure (CIWS) [3], we develop new controlled light beam splitters (and filters), the CIWS Beam Splitters (CIWS BS). Particularly interesting is that the CIWS BS developed here are realized from a pure glass components. This type of splitter is a thin flat interference structure with a thickness of ~1 mm and dimensions of ~2 x 20 x 100 mm. The essential advantage of the proposal is the control of the beam splitting power and the energy ratio (transmission-reflection, also of interest for high-power laser beams) by simply sliding the splitter in its plane. This allows keeping the direction of propagation of the formed beams. As we show, in the optimized conditions, this allows controlled linear separation over a large range, in ~ more than 50 mm, and achieving a transmission variation of ~98% to 10%. For such CIWS BS, there is no polarization requirement, no problematic dielectric and metal mirrors, it has very low light absorption and scattering, only a several percent, no humidity breakdown, the operating power is higher than MW/cm^2, CIWS BS is easy to maintain. Thus, the developed original light beam splitters, following the above, are basically competitive compared to traditional light beam splitter solutions, detailed summarized and presented in Ref. 4. In the literature are presented many useful technical developments concerning the BS apparatus, based on the known principles and elements, e.g. [4]. The developments are based on the use in light polarization designs, where polarized light is handled and polarizing elements are used, either absorption-based or multi-dielectric mirror interference designs, of diffractive beam optics [4 - 6], which have their inevitable problems and limitations, especially for their maintenance. Thus, for the scientific and technical problems discussed, as an important part of technical progress nowadays [5, 6], it is of interest to propose and develop new principles and solutions, especially of a basic character.

In the developed our proposal here, we report the analysis, computational approaches, and behavior study of the desired high-performance CIWS BS realized using only suitable pure glass composite components. We also present a verification of the correctness of the analysis. The goal is to find and demonstrate the existing conditions and prove that it is possible to achieve the claimed high-performance, competitive properties of a new optical instrument solution based on our CIWS [3], especially composed of a suitable combination of single pure glass structures.

II. CIWS IN BRIEF – PROPERTIES AND ANALYZING APPROACH

A. General

The design of the IWS is similar to that of the well-known Fabry-Perot Interferometer (FPI) [4]. The two structures, FPI and IWS, have a similar construction - air or another transparent material, such as glass, sapphire, etc., the so-called gap, which is placed between two reflective surfaces (mirrors). The mirrors in FPI are practically perfectly parallel. In IWS, where the gap is called the Fizeau interferometer or Interference Wedge (IW), the mirrors are placed at a specially chosen small angle (~10^{-5} rad). This angular difference leads to noticeable differences in the properties of the two interferometers. Both interferometers work on the basis of interference of formed multiple light beams. The properties of the FPI are well known due to its importance for a number of optical type measurements [4]. The basic properties of IW, which is a single gap IWS, are also present in the literature, but have not been as extensively studied in terms of their diversity and applicability.

Interest in IWSs is increasing in connection with the possibility of their use for application of the laser technologies. Our expertise relates to the study of IWS properties and their application in a number of laser

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solutions, for example in a new solution for single-mode dual-wavelength lasers with continuous tuning, which incorporates the fundamental properties we have discovered, such as spectrally selective non-Snell's reflection and transmission asymmetry [1-4]. As a further development of the IWS and as an important point, we have also introduced new interference wedge-type structures, the noted one CIWS [3]. It can consider this structure as a further development of the Fizeau type optical interferometry. We have shown that CIWS in a multi dielectric layer implementation can provide narrow spectral selection, e.g. ~0.01 nm, in combination with a wide tuning range of more than of 10-50 nm obtained by simply sliding of the structure [5]. We have recently shown the potential of a suitably composed CIWS system of two or more IWSs efficiently providing a very large and linear change in the transmission of the incident laser beam by simply sliding of the CIWS. This is the base for our competitive beam splitters, especially for powerful laser beams, developed in the work.

In this work, we develop our proposal to use a specially composed CIWS of only pure glass IWS component with appropriately chosen thickness, wedge angles, and superimposition as a highly efficient beam splitter, CIWS BS. The significant improvement in performance, as we have shown and implemented here, is also related to the application of our patented approach [3] to solve the beam splitter problem based on an integrated implementation, where the CIWS consists of coupling two parts of different CIWS and IWS beam splitters. It is particularly important, as we show that such highly competitive IWS-based beam splitters can only be realized with pure glass composite elements using only Fresnel reflection.

B. Short general presentation of IW and CIWS as base of the developed beam splitters

The basis of the high performance beam splitters developed in this work is CIWS as a suitable combination of IWSs. The basic, simplest IWS is a single wedged gap with reflecting sides, basically formed by multi dielectric mirrors, and here, by Fresnel reflection. It is shown schematically in Fig. 1(a). The principle of CIWS as a suitable combination of wedged gaps is shown in Fig. 1(b) in an example of CIWS with two gaps. The composing IWSs can be two, three, five and more. The relevant notations that characterize IWS and CIWS are: R_i – reflectivity of the reflective sides i; n_1, n_2, $n_{3,\ldots}$ are the refractive indices of the layers, and n_0 – the refractive index outside them; α_i is the corresponding wedge apex angle; e_i is the geometrical and $e_i^* = e_i \cdot n_i$ with $i = 1, 2, 3\ldots$ is the optical thicknesses, where n_i is the corresponding refractive index for the i-gap; θ is the incident angle for the laser beam IB with respect to IWS surface and CIWS front mirror. In this work, we consider the case of a CIWS consisting of a series of pure glass wedges (glass gaps) and an air wedge (air gap) between each glass wedge pair. In this case, the construction of the CIWS is the simplest since the inner walls of all the glass wedges are reflective surfaces of the formed air wedges with reflectivity formed by the Fresnel reflection $R=[(n_i - n_{i-1})/(n_i + n_{i-1})]^2$. We will consider one, three and five wedges CIWS, as a sequence glass wedge - air wedge - glass wedge - air wedge - glass wedge.

From the general theory of the single gap IWS, i.e. IW, it is well known that when the IW is illuminated by a parallel monochromatic beam of large size, especially a laser beam, of wavelength λ_i, the transmitted light forms along the wedge arm a series of passing parallel large or thin lines, the so-called Fizeau lines (FL). The width of the FL depends on the reflectivity of the mirrors and the wedge angle. As an illustration, two FLs formed by scattered light can be seen in Fig. 2. The single gap IWS used consists of two flat reflecting dielectric mirrors (R ~ 75%), each of which is formed by superimposed 6 dielectric layers (each 3 μm thick and with different n). The formed mirrors are separated by wedged layers with an apex angle of ~ 3×10^{-5} rad and with thickness of 20 μm each. The resonance lines FL are visualized by the scattered light around the incident beam of He-Ne laser (λ = 0.6328 μm). Each line has a width, and the notation "line" is used only to indicate the position of maximum transmission. The locations of these resonance lines are at equal distance $\Delta x = (\lambda_i / 2n) \cdot \tan\alpha$ and are related to the wedge thickness e_i at the line location by $e_i \cdot n = k \cdot (\lambda_i / 2n)$, were k ($k = 1, 2, 3\ldots$) is an integer. Each resonance line has a width that strongly depends on the reflectivity of the mirrors-side and the wedge angle. The resonant transmission around the FL maximum is the basis of interest for the beam splitting properties of the IWS. The three photographs shown in Fig. 2 illustrate the change of the IWS BS transmission as the incident beam approaches the center of the FL line. The location of the incident beam is registered by the formed spot on the IWS. A typical case of the computed transmission plots of two FL lines is shown in Fig.3 (a); the IWS parameters are given at the top of the plots.

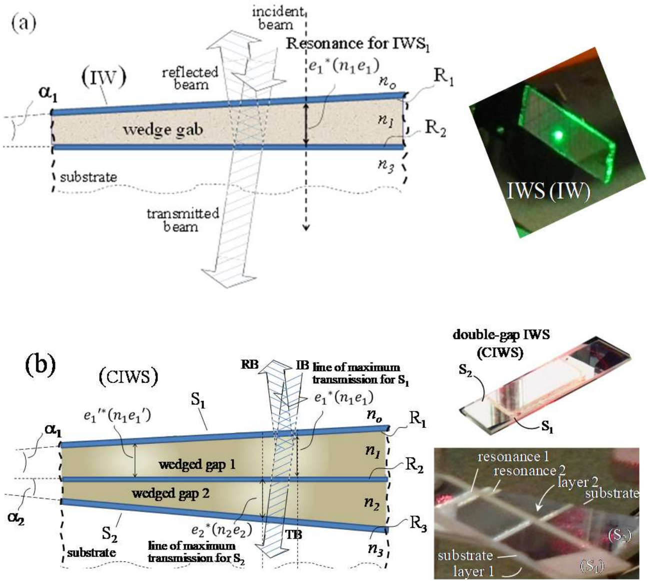


Fig. 1. (a) The basic, simplest IWS (IW), which is a single wedged "gap" with reflective sides and realization; (b) CIWS as a suitable combination of two IWSs and realization

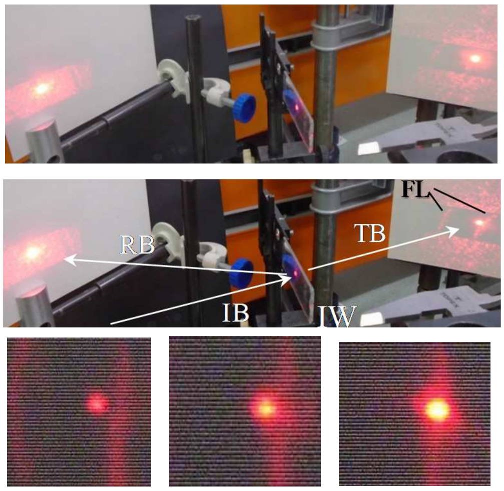
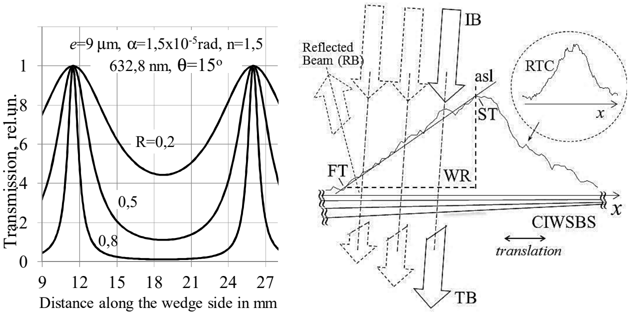


Fig.2. Beam splitting by a single gap IWS (IW) around the resonant Fizeau line; IB, RB, TB - incident, reflected and transmitted beam; red He-Ne laser, 0.6328 μm (see the text).

Fig. 3 (b) defines the important parameters of the beam splitters used in the analysis below. Let the incident beam IB have a wavelength corresponding to the FL maximum transmission condition and a smaller diameter with respect to the FL spatial width. When the IWS is sliding around the incident beam location, the IWS transmission for the beam changes. This is the principle of using the single IWS as a variable splitting. However, for an IWS to be a really usable splitter, it must satisfy two basic conditions, which are understood from Fig. 3.



(a) (b)

Fig.3. (a) Plots of single IW transmission, with two FLs shown, as a function of mirror reflectivity; (b) Schematic of a multilayer CIWS BS in resonant transmission curve RTC; ST-FT: initial-maximum and final transmission; asl - approximate line of strength, WR- working range of the splitter; IB – Incident beam, TB - Transmitted beam

The required competing parameters are (1) the ST-FT (or ST for short) separation difference varies linearly with the translation of the beam position; (2) the variation should be as large as possible, e.g. Start (maximum) Transmit ST of ~99% should drop to ~20% and lower. If the ST/WR slope is big, a large difference in the relative intensity variation in the two split beam ends will appear and as a consequence a deformation in the beam profile will occur. To realize a high-performance splitter, it is necessary to obtain a high separation difference ST and a wide working range WR. For the noted requirement, the IWS, shown in Fig. 3 (a) as a splitter, is not high performance: in the case of a small mirror with reflectivity ~ 0.2 the WR of ~ 5 mm is small, the FT is also very low up to ~ 50%; for a high reflectivity mirror the WR is very small, on the order of a few mm. A good splitter can be classified as having a WR of ~30 mm or more, with an ST of ~99% to 10% for a normal laboratory beam split of ~5-10 mm without significant deformation.

The investigations presented below allow proposing a beam splitter with high competitive parameters and, as a major advantage, to design it as a pure glass performance.

The proposed design of such a CIWS and a pure glass splitter, which is of main interest in this work, is given in Fig. 4. The composing elements are marked in the figures. The specific implementation is clarified by the schematic given in Fig.4(b). This combination in an integrated implementation via coupled FLs allows a significant increase in WR and maximum ST. We will briefly present the approaches used for analytical consideration - mathematical treatment and computer adaptation for CIWS structures, following our paper [3].

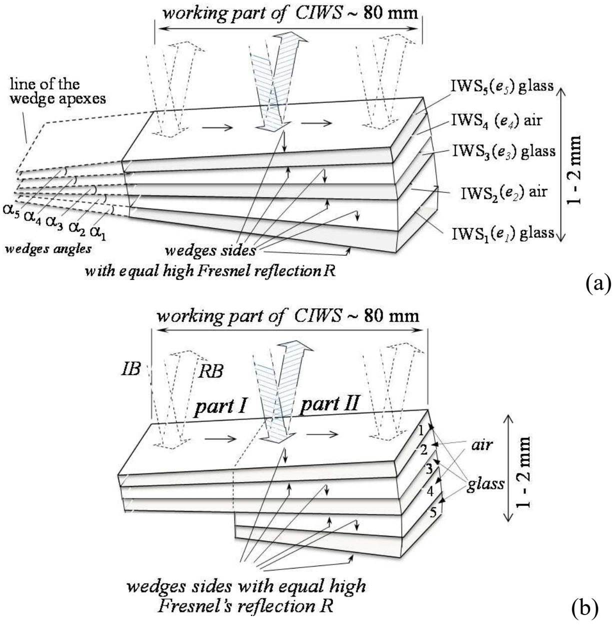


Fig.4. Schematic representation of two implementations of pure glass CIWS composed by 5 IWSs. The typical full dimensions are: thickness ~3 to 5 mm; the surface ~ 2 cm x 5 cm.

The general description of the transmission and reflection of IWS and CIWS is based on the interference of the formed multi beam funnel. Hereafter, we present the principle of both as well as details of the latter related to its computational adaptation and use. The analytical and computational calculations for IWS are possible based on our developed and published precision approach [1,3].

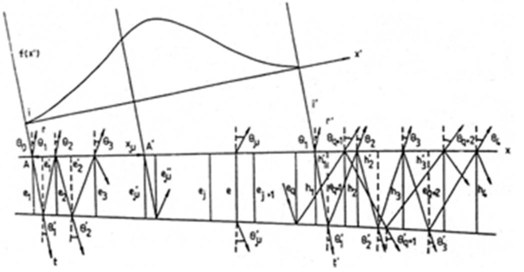


Fig.5. General approach for mathematical treatment of the IWS.

This approach [1] is related to the analytical consideration of the beam paths in the structure taking into account the complexity of the optical paths and summation accordingly. The accumulated difference in optical paths is determined for each interfering beam at a given point on the wedge surface. The distribution of the transmitted and reflected intensities $I_{T,R}(x, \lambda)$ is calculated taking into account the phase differences of the complex amplitudes of the multiple reflected beams, respectively for a given wavelength, where x is the coordinate on the surface (Fig.5). The analysis gives for the transmitted intensity:

$$I_T(x,y,z)=\alpha^2T^2\left(S_1^2+S_2^2\right) \tag{1}$$

$$S_1=\sum_{p=1}^{\infty}R^{p-1}\Omega_p\cos\varepsilon_p,\quad S_2=\sum_{p=1}^{\infty}R^{p-1}\Omega_p\sin\varepsilon_p \tag{2}$$

where Ω_p and ε_p are functions of x, z, x_0, z_0, the wavelength λ, incident angle θ, and apex angle α.

We also developed a second model to mathematically describe the action of the IWS based on a reasonable approximation of the IWS as a series of FPIs with linearly increased thickness along the wedged arms (noted as the engineering model or FPI approach) [3].

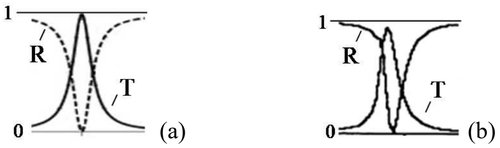


Fig. 6. The computed transmission T and reflection R around the IWS spatial resonance according to the approximate theory (a) and the exact theory (b). He-Ne laser beam (λ= 0.6328 µm) [1]. The parameters: $\theta=5^0$, $\alpha=5\text{x}10^{-5}$ rad, IWS $\theta=5^0$, $\alpha=5\text{x}10^{-5}$ rad.

For the typical case of the IWS parameters especially used in the present consideration ($\alpha \sim 0.1$-5 mrad, $\sim 0^0$-15^0), both models give well acceptable results. This FPI approach yields final formulas that are well adaptable to a computer computation. Fig.6 gives an example for the calculation of the important case of line shapes - reflection R and transmission T. The comparison between the two approaches shows very close results.

C. Engineering (simplified) analysis approach

The basic idea of this approach is to consider the IW as consisting of a series of FPIs placed close to each other along the length (arm) of the IWS. The sequence has linearly increasing (or decreasing) interferometer thickness following the thickness of the IWS. From a mathematical point of view, the approach combines the transmission expression T of the FPI [3] with our added expression for linearly changing IWS thickness. Thus, according our approach, the computer simulation combines formula (3) for the FPI transmission T:

$$T=\frac{(1-R)^2}{1-2\cdot R\cdot\cos\delta+R^2} \tag{3}$$

where $\delta=\frac{2\pi}{\lambda}2\cdot e\cdot n\cdot\cos\theta$

with the given in Fig.2 parameters, and the expression (4) for the linearly varying $e(x)$ – the IWS thickness variation:

$$e(x)=e_0+x\cdot\tan\alpha \tag{4}$$

where x is the distance from the initial thickness, which can be e_0 - the thickness of the selected IWS resonance. Thus in the expression (3) we have to use for δ

$$\delta(x)=\frac{2\pi}{\lambda}2\left(e_0+x\cdot\tan\alpha\right)\cdot n\cdot\cos\theta \tag{5}$$

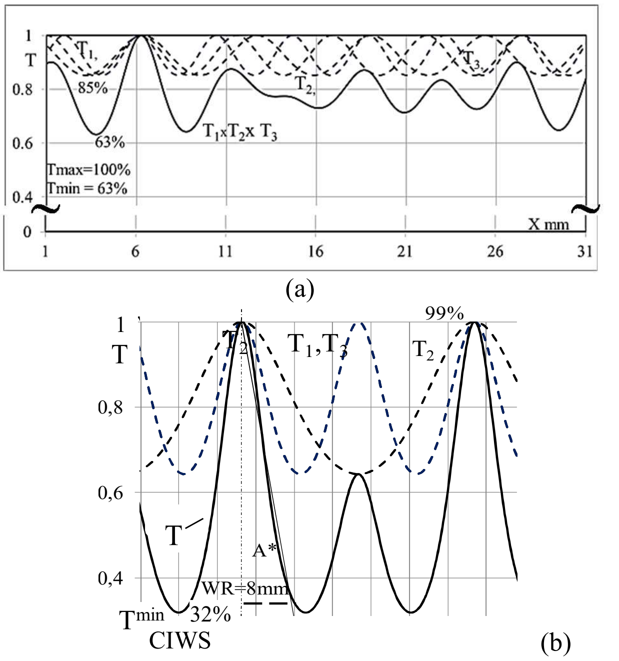
Programming (3) with (5) we can compute for given e_0 the corresponding resonance transmission curve as function of e_0, λ, θ, α, n and R. The question of parasitic losses that we considered shows that for losses up to ~3%, computational analysis by neglecting losses gives results reasonably close to the calculations for the ideal lossless cases and to those obtained experimentally.

Following our previous experience, the main focus of the discussion below will be on the combination of wedge-shaped structures of pure glass separated by air wedge layers, shown and described in Fig. 4 with the corresponding description in the text. The analysis will be for CIWS as a combination of a sequence of 5 layers: glass wedged layer – air wedged layer – glass wedged layer – air wedged layer – glass wedged layer (Fig.4) or for the first three noted layers. The layer parameters will be given for each calculated graph, i.e. for combinations of several, 3 or 5 pure glass-air wedged layers. The analysis will consider, as the main interest, the case of commercially available special heavy glass with refractive index $n \sim 2.2$, which provides a Fresnel reflection coefficient on the side of each glass layer $R_f \sim 0.14$. Other commercially available glasses with $n \sim 1.6$ - 1.8 ($R_f \sim 0.05$ – 0.08) will be considered for comparison, as well as implementations of standard glasses with low n ~ 1.5 ($R_f \sim 0.04$). The correctness of the theoretical results will be experimentally verified with appropriate experiments. The considerations are for laser light with two wavelengths, the two most common lasers Nd:YAG and He-Ne laser with corresponding wavelengths λ = 1.064 µm and 0.6328 µm, respectively.

For comparison, we first obtain the plots for CIWS composed of 3 wedged structures - $\text{IWS}_{1,2,3}$ ($R_{4,5}$ is taken as 0). The results are presented in Fig. 7. The parameters are given below the plots. The transmission of each individual IWS is given at the top of the figures with dashed lines. The index i corresponds to the parameters of IWS_i.

It can be seen from Fig. 7(a) that for the single IWS the transmission drops from 99% to ~85% for WR ~ 3 mm. For the CIWS, the values obtained range is from 99% to ~ 64% for WR ~ 3 mm. For the same CIWS design but using glass IWS with $n = 1.77$ (heavy glass) and wedges with side Fresnel reflection R=0.11 the transmission drops from 99% to ~32% for WR ~10 mm. This calculation shows the substantial increase in parameters of interest for CIWS applications.

Fig. 8, as a general representation, gives an example of the advantages of CIWS applications from multiple IWS. A CIWS composed of 5 IWS (glass-air-glass-air-glass) allows a transmission variation of 97%-47% and a WR of 19 mm; used parameters for the structures are R=0.04 and n = 1.5/1/1.5/1/1.5.



(a)

(b)

Fig.7. Transmission T of CIWS composed by three IWS (glass-air-glass) with different refractive indices of the glass, both cases for λ=0.6328 μm. The dashed lines give the transmission of each individual IWS.

(a) Solid line – the transmission of CIWS, $T_1xT_2xT_3$, with standard glass (n=1.5) and air. The parameters for the constituents $IWS_{1,2,3}$ are $n_{1,2,3} = 1.5/1/1.5$; $\theta = 5^0$; $\alpha_{1,2,3} = (5/5/4)x10^{-5}$ rad, $R_{1,2,3} = 0.04$, wedge thicknesses $e_{1,2,3,}$=(550/450/650) μm.

(b) Solid line – the transmission of CIWS, $T_1xT_2xT_3$, with n=1.77. The parameters for $IWS_{1,2,3}$ are $\theta = 5^0$, $\alpha_{1,2,3}$=1.05x10^{-5} rad, $R_{1,2,3}$=0.11 , $e_{1,2,3}$ are equal to 1 mm.

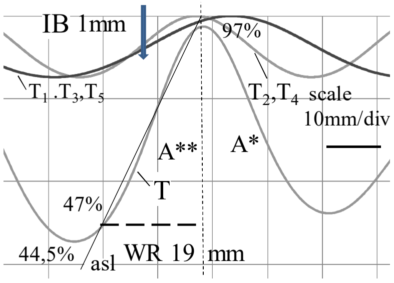
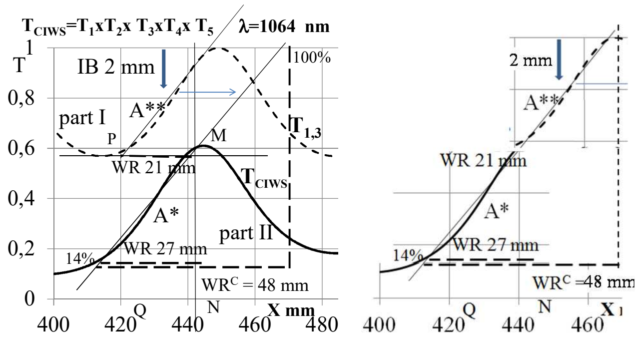


Fig.8. Transmission T of CIWS composed by 5 IWSs – 3 by the standard glass (n = 1.5) and two separating air-gap IWS.

Further development of CIWS-based controllable beam splitters is related to the solution shown below using an integral performance technique. The principle of forming the proposed controlled splitter from a pure glass integral CIWS, is shown in Fig. 9. The principle consists in combining parts of the CIWS filters and joining them with a manufacturing or mechanical technology. The basic principle can be understood from Fig. 9 and its description.

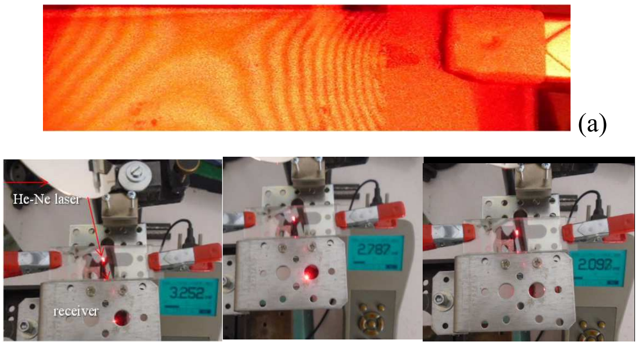
D. Experimental test of the operation of the proposed CIWS splitter

The experimental test was performed by combining as CIWS two glass IWS BS splitter tiles separated by air, with $IWS_{1,3}$ having n=1.5 (glass) and IWS_2 having n=1 (air), all with a side wall of R=0.04 (glass-air-glass splitter). The glass IWS was found by systematic examination of a large set of microscopic glasses (0.5-1 mm in thickness). The intermediate splitter has an air gap ~0.45 mm thick. The CIWS was assembled by appropriate placement of the two glass IWS plates and their appropriate separation by pressing at the end of the glass to form the IWS with the air gap. The Fizeau lines of this CIWS beam splitter structure were visualized by illuminating with a scattered portion of the He-Ne light beam, as shown in Fig. 10. A 2 mm red (0.6328 μm) He-Ne laser beam was used. For this glass-air-glass beam splitter combination, measurement from the display readings of the professional power meter gave a transmission variation of about 39% (99% to 60%), which is acceptably close to the theoretical consideration (plots in Fig. 7).



(a) (b)

Fig.9. Beam Splitter formation via our integral approach with significantly increased WR and transmission variation of ~48 mm; T from 99% to14%. (a) Principle - by combining the appropriate parts of two transmission curves - marking the appropriate parts A* of the common T_{CIWS} transmission curves and the appropriate part A** of one of the forming curves - in this case T_1 or T_3 after cutting the appropriate parts and joining these parts as shown on the (b) - forming such a CIWS Splitter.



(a)

(b)

Fig. 10. Pure glass CIWS BS. In the upper part of the picture can be seen the Fizeau lines. At the bottom, a measurement of the change in transmission of the beam splitting action of the CIWS BS is shown - the change in transmission from the relative maximum of 3.25 mW through 2.78 mW to 2.097 mW, that is a change from 90 to ~40 % , close to the theoretical treatment for the case under consideration.

The transmission of the formed CIWS BS structure is measured by its sliding with respect to the incident He-Ne laser beam, as shown in Fig. 10 (a). The transmission of the splitters and their measurement position is shown in the series of the three photos in Fig. 10(b).

III. CONCLUSION

We have reported on the development and approach for the analysis and optimization of our proposed pure glass beam splitters based on our introduced composite interference wedge structures as tools, especially for high intensity (laser) beam splitting. The linearly variable light transmission reaches from 100% to 10% and is realized by sliding the splitter plate (dimensions ~ 3 x 30 x 80 mm) in its plane. No change in direction of the formed beams, no polarization requirements, low losses, easy maintenance.

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