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To cite this article: Margarita Deneva *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **618** 012016

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Interference wedged structures as high efficient optical beam splitters – development and simple practical realization

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Abstract. Having essential experience and results, concerning Interference Wedged Structures (IWS), we have developed and practically realized optical beam splitter elements as suitably built variants of IWS. The principle of action, theoretical treatment, including computer simulation for optimization is briefly discussed. As an essential point, the technological approach for practical realization of simplest applicable Interference Wedged Based Splitters (IWBS), are carried out. The splitters are built as compact thin flat and plane, practically – sheet-like, elements with dimensions e.g. $\sim 4 \times 3 \times 0.2$ cm. They present advantages as: smooth and linear varying the power ratio between the formed beams by simple sliding of the splitter in its plane; keeping the direction of propagation of the formed beams during the control of their variations; very small losses in splitting (theoretically $\sim 5\%$); work with high power incident beams (kW/cm^2 and more for CW and MW/cm^2 for ns pulses beams).

1. Introduction

The conventional wedged type interferometers, realized as a single wedged structure of the type of Interference Wedge (IW) - solid version of the Fizeau Interferometer [1-3], present in one hand, research interest as spectroanalyser elements [1,2,4]. Such applications are due to ability of these elements to provide simplest linear dispersion for a wide spectrum light beam. The applications of the IW arrangement include also measurement of plate flatness and refractive index of substances [5]. In other hand, that is less discussed, promising type of applicability is based on the IW property for wavelength selection from illuminating, small diameter, multi-wavelengths beam, in combination with the wavelength tuning. The tuning, is by simple sliding of the IW along the plane of its surface and as results the transmitted and reflected beams keep their direction of propagation. This property in transmission [1,3] and in reflection [6] permits successively application in the laser technology as methods for laser spectral control, including effective solutions of lasers for two-wavelength generation [6,7] and for high selective and continuously tunable single-mode lasers [8,9]. Recently, we have introduced a new type of interference wedged structure – Composed Tunable Interference Wedged Structure (CTIWS), which represents suitable composition of wedged layers [10]. Such structure has essentially increased selectivity (~ 0.01 nm and better) from a multi-wavelength beam, combined with



widened tuning range (over ~40 nm and more). In the last our works, we have presented starting results, concerning investigation of the possibility the IWS to be used as splitter, which divides a laser beam with diameter permitting fully entering and translation in IWS spatial resonance (physical base and analysis) [11]. Here, we present for such type of splitter (IWBS) new results, including also the technology for practical fabrication of simple working IWBS's.

The light beam splitters are widely used elements in the range of light investigations and technology. In the literature are presented solutions [12] that are mainly of practical interest. Each of them has advantages and limitations. Shortly, for the group of compact and simple splitters, based on transparent substance doped with absorption, the limitations are constant ratio of separation and losses from the absorption, leading to heating the splitter and its cracking for high power incident beam. For the polarizing based splitting and control, limitations are work with polarized light and non-compactness of the control. For the compact group, based on variants of Fabry-Perot Interferometer (FPI) type elements (filters, reflectors), the drawbacks of typical simplest control by rotation of the elements, are change of the propagation direction of the formed beams and varying of the reflectivity of multi-layer mirrors and components. The change of power ratios for the formed beams by piezo-electric control of FPI thickness is complicated, not-compact and sensitive to parasitic influences of electrical and magnetic fields. For the compact splitters, based on separation, using optical fiber, the problem is the absence of control of power ratios and polarizing requirement for the light.

The proposed by us splitters assure precisely and variably controlled ratio of the reflected and transmitted powers by simple sliding in their planes and division with negligible energy losses. In addition to the simplicity and compactness of the construction and the control, important property of such sheet-like splitters, is power ratio control keeping the propagation direction of the formed beams, that is of essential interest for applications in optical schemes with complex. No polarization requirements are related with the splitter work. For splitter built from optical layers with high light damage resistivity, the work with the beams of power densities of kW/cm² and more for CW, and MW/cm² for pulses with ns duration is possible. In general, any solution of splitter element presents advantages and limitations. For specific application in given problematic, a given solution of the splitter can be of competitive interest. Thus, the development of new solutions of optical splitting elements with new properties or improvement, are constantly actual problematic [13].

2. IW as physical base of IWBS. Discussion of creation IWBS with application of IW

The IW that is simplest interference wedged structure is a single wedge gap with reflective sides (figure 1a). In the pictures are schematically given the obtained transmitted and reflected beams after division of the incident beam. Here R_1 , R_2 mark the corresponding reflection sides of the wedge layer and gives their reflectivity; n_1 is the refractive indexes inside the layer-gap, n_0 , n_3 of outside and of the support; α is the wedge apex angle and $e_1 \cdot n_1 = e_1^*$ is the optical thickness of the gap in the marked resonance (e_1 is the geometrical thickness). The figure represents part of the wedge around the given resonance. Following the theory of IW, along the line, perpendicular to the wedge apex, is disposed a sequence of the transmission resonances of the wedge. Each resonance is relatively narrow spatial region with high transmission in comparison to the distance between the resonances. The resonance condition for the position of the resonance line of maximum transmission is $k(\lambda/2) = e \cdot n \cdot \cos\theta$, where $e \cdot n$ is optical thickness in the considered point, θ - incident angle, λ - wavelength of the illuminating beam (monochromatic) and k is the integer $k=1,2,\dots,20$. With some losses, mainly due to the absorption and scattering in the layer and mirrors, the non transmitted part of the incident beam, is reflected. Theoretically, for ideal gap and mirror, all power of the incident light is divided between the transmitted and reflected beams. The graphs of the transmission and reflection curves for ideal IW (without absorption and scattering), computed on the discussed below FPI approach for treatment of IW are plotted in figure 1(b). The discussed division of the power between the reflected (R) and transmitted beams (T) can be seen. Two sequent resonances are shown.

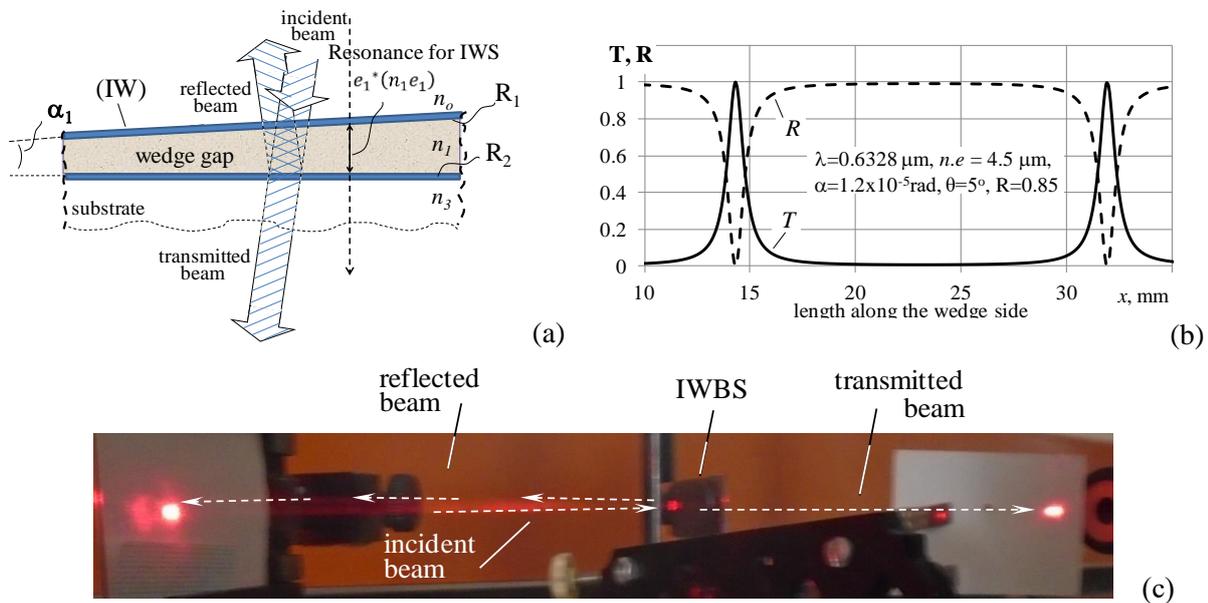


Figure 1. (a) Schematic of IW. R_1, R_2 mark the reflection sides of the wedge layer and gives their reflectivity; n_1 - refractive index inside the layer-gap, n_0 and n_3 - of outside and of the support, respectively; α is the wedge apex angle and $e_1 \cdot n_1 = e_1^*$ is the optical thickness of the gap in the marked resonance (e_1 is the geometrical thickness). The figure represents part of the wedge around the given resonance. (b) –Typical transmission and reflection curves for ideal IW; (c) – division of the incident light beam (from He-Ne laser, 0.6328 μm line)

The transmission resonance is not single thin line - it has, around the maximum transmission, some spatial distribution, presented by a resonance profile curve and described by the IW theory [1]. The precise theoretical treatment of IW is relatively complicated [3,8] and no so simply adaptable for all treated cases. As we have shown in [14] there is the possibility for simplified treatment of IW with acceptable for practical evaluations precision. We have developed simplified model to describe mathematically the action of the IW (single layer-gap IWS) and combination of two layers IWS on the base of FPI theory [1]. The basic idea is to consider the IWS as sequence of FPIs with linearly increasing (or decreasing) thickness located one to other along the line, perpendicular to the wedge’s apex – axis x . The given comparison in [14] between the results for particular cases, obtained using the discussed approach and exact theory of IW [3,8] and the experiment, shows that such approach permits evaluation with acceptable precision in practical interesting cases [14]. As illustration, some calculated graphs, following the discussed FPI approach (a) and the exact theoretical treatment (b)-(d) are plotted in figure 2.

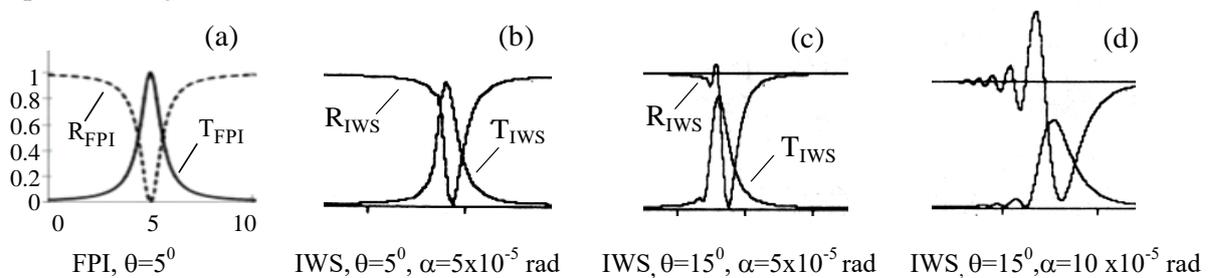


Figure 2. Computed transmission T and reflectivity R around the spatial resonance of IWS, calculated by use: (a) the approximation with sequences of continuously variable thickness FPI and (b) – (d) - the exact theory, given in [3,8]; for all graphs $\lambda=0.6328 \mu\text{m}$, $e=20 \mu\text{m}$, $R=0.9$.

The approach is convenient for use of layers with relatively small thicknesses (of ~1 to 50 μm) and angles (of few to ten μrad , beam incident angles of ~ to 10 angular degrees). The comparison between (a) and (b)–(d) leads to the noted above range of acceptable correctness for the simplified FPI approach. In the noted limits, this contributes essential part in important for the practice applications of wedged interference structure, including also the analysis of the proposed by us beam splitters. Thus, for analysis of resonance of IW we will apply the computer simulation using combination by the formula (1) [1] for FPI transmission and the property of IW to have linear variation of the thickness $e_1(p)$ with distance along line perpendicular to the wedge apex – i.e. axis x - formula (2). Here p is distance from starting thickness e_0 – the last being taken the thickness of given chosen resonance – expression (2).

$$T = (1 - R^2) / (1 - 2.R.\cos\delta + R^2), \quad (1)$$

where T is the FPI transmission, R reflectivity of the mirrors and $\delta = (2\pi / \lambda).2.e_1.n.\cos\theta$ [1], with λ - wavelength, θ - incident angle and n - refractive index.

$$e_1(p) = e_0 + p.\tan\alpha \quad (2)$$

From (1) and (2) we obtain

$$\delta = (2\pi/\lambda).2.(e_0 + p.\tan\alpha).n.\cos\theta \quad (3)$$

Programming (3) we can compute the corresponding resonance transmission curve as function of λ , p , θ for given e_0 , α and n (or can work with optical thickness of $e^* = e.n$, taken $\tan\alpha = \lambda/2.n$). Note that from (3) directly follows that the resonant thicknesses $e = e_{0k}$ for maximal transmission, wavelength λ , α , n and θ are related with the expression $k.(\lambda/2) = e.n.\cos\theta$ with k being integer 1,2,3 ... (from δ to be equal of $k.2\pi$, i.e. $\cos\delta$ to be 1).

We will consider the case of beam splitting of the illuminating beam with smaller diameter with respect to the width of resonance lines, and incident point that can move inside the resonance line along the structure (figure 7, below). In this case, sliding the wedge in its plane, the transmission can vary – if the incident point moves away from the maximum, the transmission will decrease and vice-versa. The IWS itself - if it is illuminated by larger laser beam than the width of the resonance, it can transmit part of the incident light that coincides with the resonance (resonances) and will reflect the other part that is outside of the resonance, thus to split the beam. Such simplest splitting in practice can deform strongly the reflected and transmitted beams compared with the incident beam. This will have limited use to give information about power variation in the incident beam, using the observation of only one part of it [15].

We will follow the idea of splitting by moving the small size beam inside the large resonance. To obtain good splitting, the splitter must have large resonance width for splitting the large diameter incident beams and linear decreasing of the transmission of the wing – the last will permit linear decreasing of the transmitted power (and increasing of the reflected). Thus, it is necessary the IW to have such type resonances – with long and linear wings. The computed resonance curves of IW of the dependence of reflection R , using the expression (1) and (3) are given in figure 3 (with used parameters in it).

The wedge thickness e^* ($e.n$) practically has no influence on the width of resonance curves that show from the analysis based on the expressions (1) and (3). The wedge angle α is chosen realistic for technological realization (2.1×10^{-5} rad). The incident angle θ is enough smaller, less than 10° , permitting separation of both formed reflected and incident beams. One IWS structure can be used as beam splitter for many wavelengths because different wavelength resonances enter in the length of the IWBS (of few cm) for different order k . For calculations, realistic parameters of $e_0.n$, α , λ (He-Ne laser) and θ are chosen. The reflectivity of the mirrors is parameter, given as part of the maximal value of 1. The curves show that, the needed resonance behavior of IW for good splitting can be obtained for relatively low reflectivity ($R \sim 0.15 - 0.35$; the transmissivity is also given as part of 1 (1 corresponds to 100%). Note that the maximum transmission for light incidence of 0° is 1 in the used approach for the treated IW(FPI-theory). For exact theoretical analysis [3,8] it is less – of ~ 0.96 . In practice, due to the absorption and scattering in the real layers and Fresnel reflection the transmission is lower. In our

investigation the maximal obtained transmission is value of 83% for IWS that we have, with full losses of ~10 %.

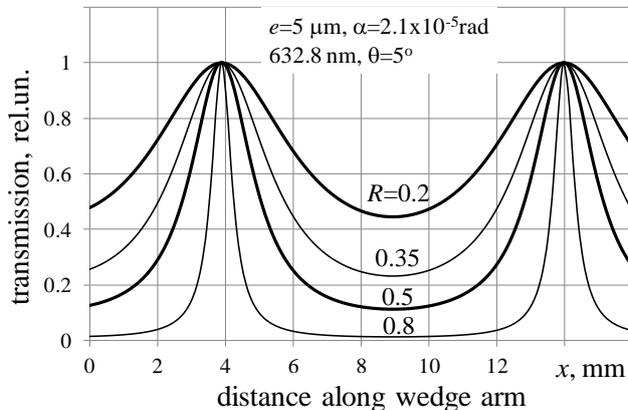


Figure 3. The computed resonance curves of IW: the dependence of reflection R , using the expression (1) and (3).

division of relatively large diameter incident beam; acceptable slope of the line of decreasing/increasing of the transmission that provide lower or negligible deformation of the spatial intensity distribution in formed beams; difference of variation of the transmission at the start and the end of this line to be sufficient for the practical use of splitter.

3. IWBS fabrication as solid, flat sheet-like and compact construction Experimental Investigations of laboratory realized working IWBS.

3.1. Dielectric layers fabrications

Following the discussion in point 2, we have fabricated the laboratory working samples of IW with discussed parameters that are most suitable, as it is possible, in our conditions to work as good IWBS. The described already models, that approach this requirement and the component of which is realistic for production, was used for experimental investigations.

To compose the IW we use as wedge gaps air-gaps with thicknesses of ~5 μm , closed between two TiO (or TaO) layers of thickness ~ 0.22 μm . We specially creates the wedged structures with noted characteristics to have low reflectivity (~ 0.15 -0.5) and thus to be with a large spatial resonance, that was discussed already in section 2. The TaO and TiO, fabricated by DC reactive magnetron sputtering in vacuum were chosen as very resistive of internal influences layers. The produced layers, using such technique, are with good mechanical properties and resistivity (especially compared to these ones, producing by vaporization or chemical layering).

The technology was the following. The sputtered cathode Ti with diameter 100 mm and thickness $d = 5$ mm was made of pure Ti (99,8 % brand BT 1). The sputtered cathode Ta with diameter 100 mm and thickness $d = 6$ mm was made of pure Ta (99.95 % brand TVCH). Depending on the specific requirements of the analytical techniques used, the layers were deposited on substrates of microscope polish glass (DELTALAB – Spain) with dimensions 40 \times 26 \times 1 mm. Prior to the deposition, the substrates were sputter cleaned for 10 minutes - working pressure $p_{\text{Ar}} = 8$ Pa; discharge voltage $U = 1050$ V; current $I = 0.1$ A. The films were produced in the Titan 22 (Bulgaria) high-vacuum installation under the next regime parameters. For TiO: lowest pressure value $p_1 = 1,5 \times 10^{-3}$ Pa; working pressure - reactive gas (O_2), $p_{\text{O}_2} = 5,5 \times 10^{-2}$ Pa; discharge voltage $U = 420$ V; discharge current $I = 1$ A; substrate temperature $T = 180$ C $^\circ$; cathode – sample distance $H = 120$ mm; deposition time $t = 60$ min.

For TaO: lowest pressure value $p_1 = 1,5 \times 10^{-3}$ Pa; partial pressure (Ar), $p_{Ar} = 1,0 \times 10^{-2}$ Pa; working pressure (Ar + O₂)n $p_{tot} = 5,6 \times 10^{-2}$ Pa; discharge voltages $U = 535$ V; discharge current $I = 1$ A; substrate temperature $T = 20$ C°; cathode – sample distance $H = 120$ mm; deposition time $t = 60$ min.

The layers was layered on the flat glass supports ($\sim 4.5 \times 3$ cm) with thicknesses of 0.1 cm The reflectivity of single layer on the glass support was ~ 0.20 , measured for wavelengths – red (0.6328 μ m), yellow (0.5941 μ m) and green (0.532 μ m).

3.2. The IWBS construction, operation, useful properties and limitations.

The described layers with reflectivity of ≈ 0.2 are specially producing to be very convenient as layer-mirrors $R_1 = R_2$ for creating the IWBS with desired long line of transmissivity variation. The schematic of the simplest constructions used was shown in figure 4(a). The two supports (see end of subsection 3.1), turned with the layers to be one to other, were separated at the one end by ~ 3 μ m special foil and in the other - at 4.5 cm – with 4.5 μ m thick foil, thus the wedge angle to be $\sim 3 \times 10^{-5}$ rad. The composition of plate with the layers and spacer was adjusted by suitably pressing in homemade mechanism (figure 4b) that permits easy variation of the wedge angle, or and glued variant to represent solid, flat sheet-like and compact construction (figure 4c), with the given above dimensions of the supports. In figure 5 real photograph of experimental installation using the described simples of IWBS is presented.

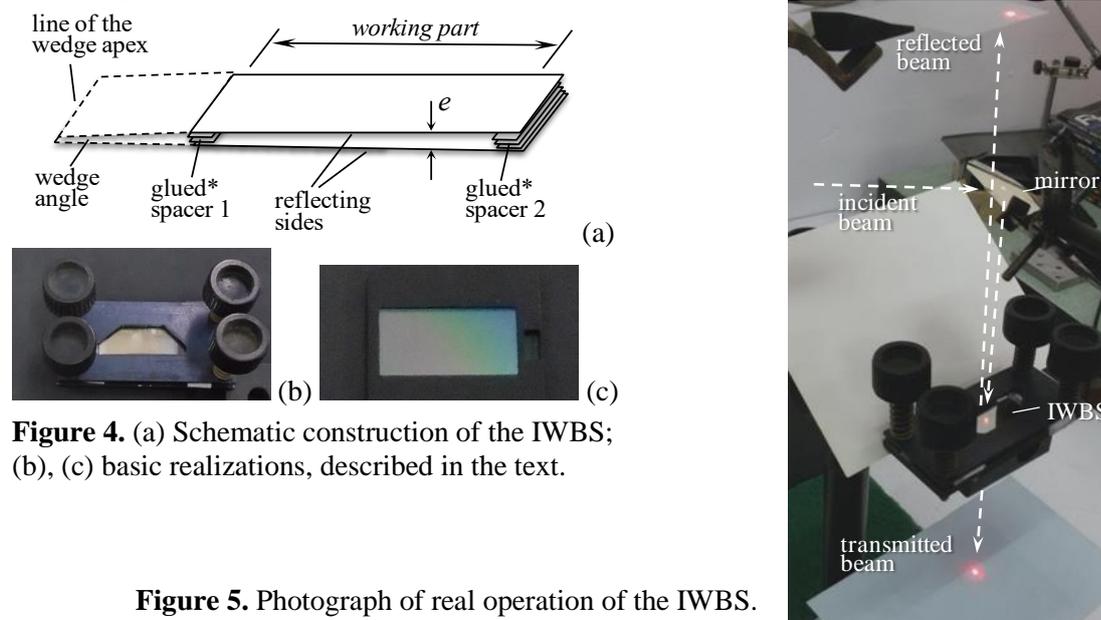


Figure 4. (a) Schematic construction of the IWBS; (b), (c) basic realizations, described in the text.

Figure 5. Photograph of real operation of the IWBS.

From the graphs in figure 3 we can estimate that for $R \sim 0.2$ (0.15-0.25), the range of linear variation of transmission is ≈ 4.5 mm, the last permits to control splitting for the beams with diameters \varnothing to 2.5 mm (net range 4.5– \varnothing mm, i.e. 3.5–2 mm). The variation – decreasing/increasing of the transmitted power is smooth and linear between maximal of $T \approx 0.67$ and minimal $T \approx 0.33$ and with the beam diameter width (i.e. for the He-Ne Gaussian laser beam with Gaussian diameter, of 1.4 mm,). Note that, measuring the reflection, transmitted and incident power, we have estimated the losses in the prepared IWBS. For incident beam power of 1.6 mW, transmission power was measured to be 0.672 mW and reflected of ~ 0.66 mW. The corresponding losses are estimated to be 0.18 (18%). Thus good quality of the layers is important for IWBS work.

The main series of experimental investigation was made with the compact IWBS with vertical disposition of IWBS, as it is shown in figure 5. In figure 6(a) is plotted photographs of the TaO layer on the glass supports used to created the IWBS with fixed mirrors (dispositive in figure 4c). The

formed large Fizeau fringes are shown in photograph in figure 6(b). In general, they have some distortion, however the aim of the IWBS to be used with small beam diameter (~ 1 -1.5 mm) permits to be selected good part for IWBS work – the last shown with dashed rectangle in figure 6(b). This spatial range permits good work of IWBS. In figure 6(c) is given the graph of the working range, where in the bottom – the selected resonance in expanded scale for beam-splitting. The series of photographs of splitting of incidence beam (IB) by sliding of the IWBS are shown in figure 7(a)-(c) that illustrate the change of the position of point of incidence of the beam with respect to change the position of the resonance line – line of maximal transmission. The variation of the transmission is well evident from the figure - the spots in increased scale are shown in figure 7 (a',b',c'). The graph (d) shows variation of the transmission when the incident beam (diameter of 1mm) moves toward the maximum of the transmission in selected resonance. The unit of 1 mm for the scale is marked. Finally, in figure 7(e) are plotted real graphs for controlled beam splitting of the incident beams of 1 mW – for the transmitted beam – transmission T and for reflected – R . The spot for the smaller slope of transmission of curve RL (figure 7d) reproduce well the intensity distribution of the incident beam.

The graphs show real applicability and potential of the developed technique for controlled beam splitting and opportunity for easy organizing fabrication of such IWBS.

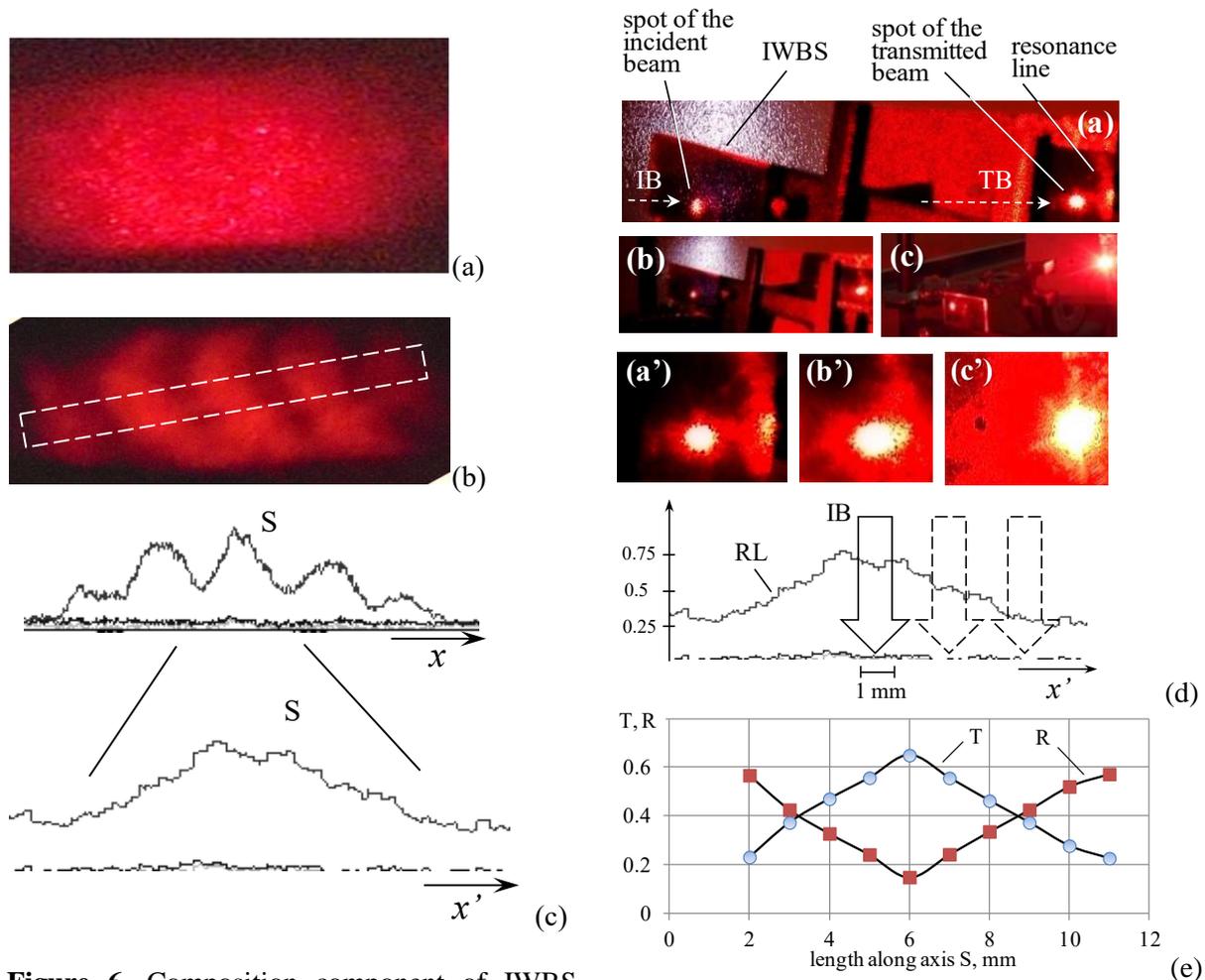


Figure 6. Composition component of IWBS and large interference resonances for the described IWBS realization; (a) layers; (b) composition and resonances; (c) – expanded resonances.

Figure 7. Beam Splitting with developed IWBS. Schematic of splitting and Graphs of controlled powers in the transmitted and reflected beams, obtained by separation of the incident beam.

4. Conclusion

In the work we have presented the developed and practically realized by us new beam splitting element, based on interference wedged structure (IWBS). The IWBS present advantages such as: the splitters are built as compact thin flat and plane, practically – sheet-like, elements. They assure smooth and linear varying the power ratio between the formed beams by simple sliding of the splitter in its plane; keeping the direction of propagation of the formed beams during the control; very small losses in splitting (theoretically zero); work with high power incident beams (kW/cm^2 CV, MW/cm^2 for nanosecond pulses). The developed of new solutions of optical splitting elements with new properties or improvement, enriches the variety of beam splitters and the choice for consummators’.

Acknowledgment

This work was supported by Bulgarian Science Fund, project DN-17/7 “Elements and devices in optics and quantum electronics on the base of wedged interferential structures for laser technology, optoelectronics, optical communications, metrology and spectrum analysis.”

References

- [1] Demtredner W., 2008 *Laser spectroscopy*, Springer, 4th ed.
- [2] Kajava T, Lauranto H and Saloma R 1993 Fizeau interferometer in spectral measurements, *J. Opt. Soc. Am.* **B10**, pp 1980 – 1989
- [3] Stoykova, E and Nenchev M 2010, Gaussian Beam Interaction with Air-gap Fizeau Wedge, *J. Opt. Soc. Am.* **27**, pp 58-68 and the literature cited therein
- [4] Siddique M, Yang S, Li Z, Li P 2007 Fizeau interferometry for THz-waves' frequency and intensity measurement, *J. Beijing Institute of Technology* **16**(3), pp 326-329
- [5] Kumar Y and Chatterjee S 2009 Simultaneous measurement of refractive index and wedge angle of optical windows using Fizeau interferometry and a cyclic path optical configuration *Applied Optics* **48**(24), pp 4756-4761
- [6] Nenchev M. N and Meyer Y H 1981 Two-wavelength dye-laser operation using a reflecting Fizeau interferometer *Applied Physics* **24**, pp 7-9; 1984 Laser tuning with combined system of Interference wedges, *Proc. SPIE* 473, p 181
- [7] Deneva M, Uzunova P, Nenchev M 2007 Tunable subnanosecond laser pulse generation using an active mirror concept *Optical and Quantum Electronics* **27**(39), pp 193-212
- [8] Stoykova E and Nenchev M 2001 Fizeau wedge with unequal mirrors for spectral control and coupling in a linear laser oscillator-amplifier system *Applied Optics* **40** pp275402-5411 and the literature cited therein
- [9] Nenchev M N and Meyer Y H Continuous-scanning system for single-mode wedge dye lasers, *Optics Letters* **7**(5):199-200, DOI: 10.1364/OL.7.000199
- [10] Nenchev M, Stoykova E and Deneva M 2018 Composite wavelength tunable wedged interference structures with increased free spectral range *Optical and Quantum Electronics* **50**(12) DOI: 10.1007/s11082-018-1668-9
- [11] Deneva M, Nenchev M and Stoykova E 2019 Interference wedged structures as light beam splitting elements *Proc. of SPIE* Vol. 11047, 110471G, CCC code: 0277-786X/19/\$18, doi: 10.1117/12.2516696
- [12] RP Photonics Encyclopedia, https://www.rp-photonics.com/beam_splitters.html
- [13] Turner M D, Saba M, Zhang Q, Cumming B P, Schröder-Turk G E and Gu M 2013 Miniature chiral beamsplitter based on gyroid photonic crystals *Nature Photonics* **7**, pp 801–805
- [14] Nenchev M, Deneva M and Stoykova E 2019 Competitive light wavelength division multiplexing element based on tunable interference wedged structures *Proc. of SPIE* Vol. 11047, 110471F, CCC code: 0277-786X/19/\$18, doi: 10.1117/12.2516698
- [15] Beers Y 1974 The Theory of the Optical Wedge Beam Splitter, *U.S. Government Printing Office Washington, Nat. Bur. Stand. (U.S.), NBS Monogr.* 146, 31 pages