Integrated interference wedged structures as a basis for creating compact light beam splitters with improved parameters

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Integrated interference wedged structures as a basis for creating compact light beam splitters with improved parameters

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Abstract. Based on the idea of combining in one plate and in a puzzle-type of properly designed parts of planar sheet-like interference wedged structures (IWS), including the composed interference wedged structure (CIWS) developed by us, we show the possibility of realizing new integrated light beam splitters (for laser beams) that have useful competitive properties. Using our theoretical approach for analysis of IWS, simulations and test experiments, we show that such optimized splitters ensure a smooth splitting in an increased linear variation range of the transmission T (from ~ 80 – 95% to 5%) and reflection ($R = 1 - T$), in combination with a large working range (linear splitting by sliding to more than ~15 – 20 mm). The low slope of the transmission variation permits one to split beams of diameter 3 – 5 mm; focusing the beam increases this range to more than ~15 mm. The control is performed by sliding the splitter in its plane (dimensions ~ $5\times2\times0.1$ cm^3) thus conserving the direction of the formed beams. No specific polarization is required and the use is possible of high-power laser beams. A suitable practical realization is the use of a mask technology for sequential deposition of necessary layers in integrated circuits.

1. Introduction

The interference wedged structures (IWS) [1, 2] are a type of interference structure that has applications as spectral analyzing elements and in metrology. In previous works, we have developed interesting and useful new possibilities for their applications in the laser technologies as elements for laser spectral and directional control: two-wavelength lasers, continuously tunable single mode lasers [3-4]. Recently, we introduced a new structure of this type – a composed tunable interference wedged structure (CTIWS) [5], which offers a possibility for spectral selection of a narrow line (e.g ~ 0.01 nm) in combination with a large tuning range of more than 10 – 50 nm). Such a structure, as we have shown, has an important potential of application in realizing wavelength division multiplexing elements for optical communications systems that select a desired wavelength with a controlled power from a multi-wavelength beam [6]. Other potential application of IWS, proposed by us, is using them with suitable parameters and compositions as light beam splitters – interference wedge beam splitter (IWBS), as discussed in detail in Ref. [7]. Such use, discussed in the present work, is based on the variation of the transmission around the position of the resonance line implemented by a simple sliding of the structure along the wedge(s) arm(s) [7]. Importantly, the direction of propagation of the formed beams does not change as the division ratio is varied. The practical application of this idea requires that the appropriate composition, parameters and design should be found.

In the present work, we report the development by using theoretical considerations, simulations and experiments of a type of IWBS – including CIWS, and propose new IWBS devices – integrated laser light beam splitters and filters that exhibit significantly improved operating characteristics – increased difference of the splitting percentages – from ~5% to ~99%, and a wider working range (i.e., the length of translation of IWBS needed for a desired change of transmission) that also leads to a small slope of the transmission change. The smaller the slope, the smaller the deformation of the formed beams cross sections. In general, when discussing optical beam splitters (including their use as filters), we have to note that such elements are well familiar in any scientific or practically-oriented optical laboratories, as well as medical laboratories and industrial institutions, especially those using lasers. The existing realizations of beam splitters can be found in the Internet and in the literature and are also shortly discussed in [7]. Each of them has advantages and limitations. Thus, any new solution concerning splitters that adds competitive properties is of current interest, particularly when solving a given problem necessitates a specific optimal solution.

2. The IW and the CIWS as a basis of the beam splitters developed

In the work, the new solutions developed of interference wedged beam splitters are based on interference wedged structures (IWS) in their simple realization – the interference wedge (IW), and as suitable combinations of such wedges – composed interference wedged structure (CIWS). The IW is a single transparent wedged layer (wedge 'gap') with reflective sides (mainly implemented as multi-dielectric mirrors), as schematically shown in figure 1 (a).

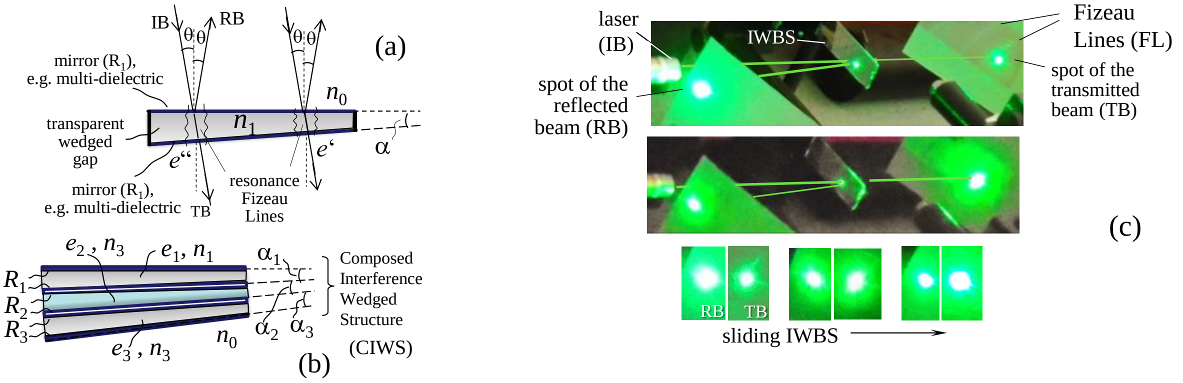
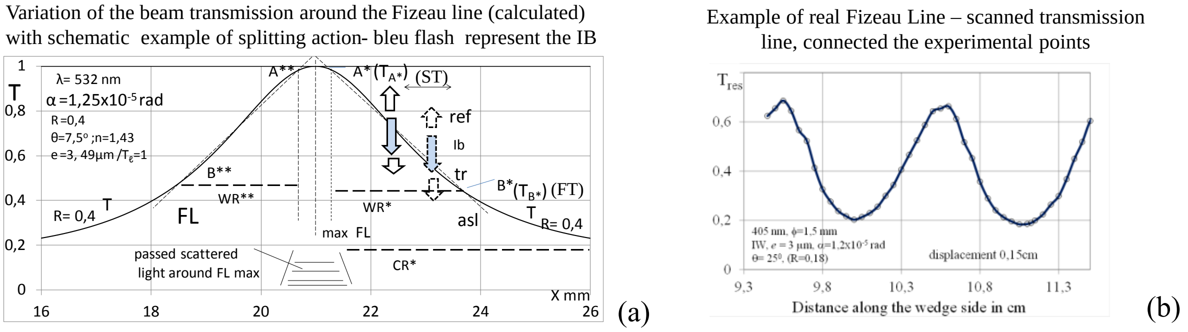


Figure 1. Schematic of the single gap IWS (IW) and of the composed IWS (CIWS) and photograph of IW operation. The notations are given in the figures and in the text below.

The notations in figure 1 are: R_1, R_2 and R_3 for the reflective sides ($R_{1,2,3}$ denoting the corresponding reflectivity), n_1 ,n_2 and n_3 are the refractive indices of the layers, n_0, is that 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 thicknesses for the gaps at point *i*. The incident angle for the laser beam IB with respect to the IW front mirror is θ. In practice, the IW, in the more convenient for applications realizations as a flat thin construction (dimensions, e.g., 5×2×0.1 cm^3), is a mirror on the transparent lame-support (~ 1mm), a dielectric wedged layer deposited on the support with a thickness of ~μm, and then on its surface, a layered multi-dielectric mirror. Figure 1(b) shows schematically the CIWS as consisting of IWs with suitable parameters and positions. The notations are the same as for the IW (in figure 1 (a)). Figure 1 (c) is a photograph illustrating the operation of an IW.

From the general theory of IW [1, 2] it is known that an IW has along the wedge arm a relatively narrow in length sequences of places of transmission in the form of lines parallel to the wedge apex; their positions depend on the wavelength and the IW parameters. These are known as Fizeau lines

(FL), or lines of maximal transmission; however the FLs width is of importance in view of potential applications. Figure 1 shows the central line of maximum transmission formed by scattered light when the laser beam is incident on the IW surface (also the spot of transmitted light). Figure 2 (a) is the computed curve of the transmission *T* for FL around its maximum.


Variation of the beam transmission around the Fizeau line (calculated) with schematic example of splitting action- bleu flash represent the IB

Example of real Fizeau Line – scanned transmission line, connected the experimental points

Figure 2. Calculated curves of IW transmission at the Fizeau lines and a real line.

The figure illustrates also the principle of the IWBS. The incident beam IB with a variable place of incidence relative to the maximum of the line is presented by the arrows. Changing the place of incidence by sliding the IW (or the beam) around the maximum of the FL changes the transmission (and reflection), i.e., the splitting ratio. For applications in beam splitting elements in particular, it is desirable to have a wide line, which is one of the essential characteristics of the splitters (in combination, however, with other characteristics, as discussed below). A CIWS (figure 2 (b)) that is a suitable combination of wedged gaps of dielectric layers, or of air or glass gaps, placed between partially reflective surfaces permits considerably more variants of combinations to obtain improved Fizeau line parameters needed for the good work of the IWBS. Let us briefly define what is "good work" of the IWBS, the achievement of which is the aim of this work, including the use of CIWS.

Of general interest are the following physical parameters: (*i*) linearly decreasing transmission *T* (linearly increasing reflectivity *R*) with linear variation of the splitting ratio. The higher the difference between the transmission maximum $T^{\max}$ and minimum $T^{\min}$ in % (initial ST and final FT transmission), the better is the splitter functioning. (*ii*) the working range (WR in mm) that is the length of the projection of the line ST-FT on the axis of translation and (*iii*) the slope of the ST-FT line – (ST-FT)/WR in %/mm. The splitting is good in the case of a wide WR and a small slope *t*, because of the smooth control and the small deformation of the beam due to the transmission difference in the WR ends. Also, a natural property of IWBS is that the direction of propagation of the formed beams remains unchanged during the power ratio variation; further, there is no polarization dependence and the construction is very compact.

3. Analytical approach

We have developed a simplified approach to describe mathematically the operation of the IWS [7]. It is well suited to the limits set in [7]. The basic idea is to consider the IW as consisting of a sequence of Fabry-Perot Interferometers (FPI) with a linearly increasing (or decreasing) thickness, located next to each other along a line perpendicular to the wedge's apex. Mathematically, the approach combines the expression for the transmission *T* (equation (1)) of Fabry-Perot interferometers [1] with an expression, added by us, accounting for the linearly increasing thickness of the IW (equation (2)).

Thus, the computer simulation combines equation (1) [1] for the transmission *T* of the FPI and the expression for the variation *e*(*x*), where *x* is the distance from the initial thickness, which can be e_0, or the thickness of the chosen resonance (equation (2)):

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

with $\delta = (2\pi/\lambda).2.e.n.cos\theta$ [1] with the parameters given in figure 2. Concerning the parasitic losses, they are assumed to be less than ~ 3 %; when the losses are neglected, the computer analysis yields results acceptably close to both a lossless case and to experimentally obtained results. From the IWS thicknesses variation we have $e\ (p) = e_0 + x.\tan\alpha$.
Thus, in the expression (1) we substitute for δ:

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

Solving (1) with (2), we can compute for a given e_0 the corresponding resonance transmission curve as a function of e_0, λ, p, θ, α , n and R.

4. Study on the traditional approaches limitations in achieving the needed combination of a high difference between the initial and final transmissions and a wide working range

The standard approach to obtain a wide resonance is to use a low-reflectivity mirror IW and small wedge angles. However, as we illustrated in figure 1, such a solution does not lead to an improvement of the IWBS characteristics. As can be seen in the typical graphs (also shown by our detailed analysis), low-reflectivity mirrors produce large resonance curves, but, as shown in figure 3 (a), with a high final transmission, especially for the linear part of the transmission curves (up to ~ 40 %). Let us also note that when a high-reflectivity mirror is used, the linear part ends at a relatively high reflection, which drastically decreases the WR. The same situation with a low final reflectivity characterizes the application of a small angle – typical curves are shown in figure 1 (b). The use of small angles is also related with technical difficulties in producing very smooth layers (a small thickness variation leads to non-linear resonant thickness variation and, respectively, to a lack of control over the transmission variation).

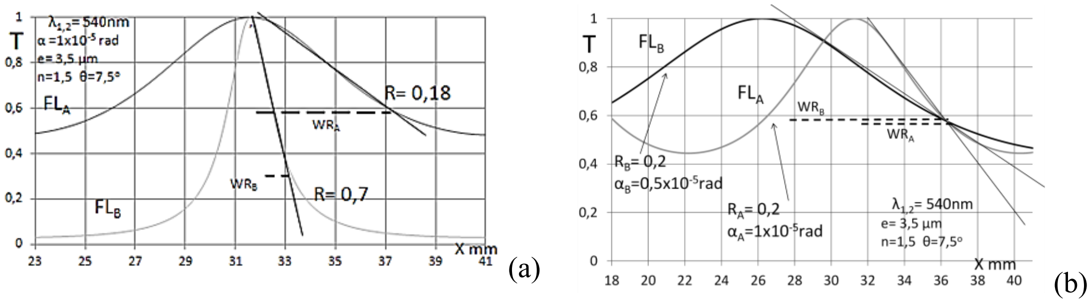


Figure 3. (a) Transmission curves for two mirror reflectivities ($R_A = 0.18$, $R_B = 0.7$; $\alpha_{A,B} = 1\times10^{-5}$ rad) and (b) for two wedge angles ($\alpha_A = 1\times10^{-5}$ rad, $\alpha_B = 0.5\times10^{-5}$ rad, $R_{A,B} = 0.2$).

5. Our proposal and its implementation

During our work, we found that for the composite structure we can obtain interesting properties – typically, the transmission curves of a composing structure have a very low final transmission; however, the working range is also relatively small. This is illustrated by the graphs in figure 4, where the transmission curves T_2 of one of the composing IW are presented by a dotted line and the transmission curve of the CIWS, by a solid line, and are formed as the product $T_1\times T_2\times T_3$ of the transmissions of the three composing structures with the parameters shown in the figure. One should note the considerably low final transmission of CIWS and the considerably high WR of T_2. It is also seen that the slope of the transmission curve of the single composing structure and of the composed structure are in excellent coincidence (the slope of the part of these curves).

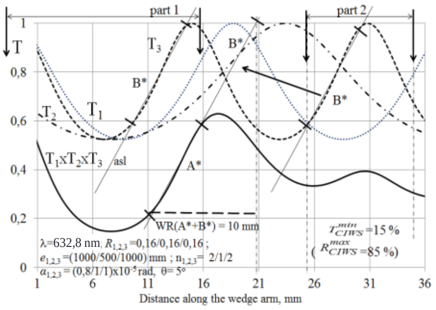


Figure 4. Graphs of the transmission of selected composed IW structure (T_2) and of the composed IWS structure.

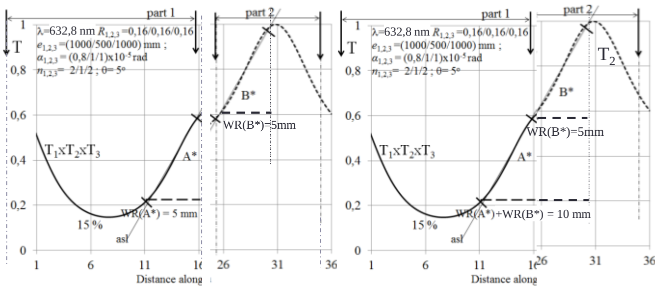


Figure 5. The two composing parts of the graphs from figure 4 (left – two separate parts, right - joined parts).

This leads to a possibility to take parts of the two structures with equal slopes – from the composing one and the composed one realized in separate plates (or in a single plate, using a mask technology) and to connect spatially these two parts. Thus, we can obtain a combination with very useful parameters – a strongly increased transmission (more than twice) and a more than twice wider working range, as can be seen in figure 4. The two graphs are plotted by approximating a straight line that coincides very well with the linear parts of the two curves. Implementing separately these two parts (figure 5) – the first (A*) as a part of one of the composing structures, and the second (B*) of the composed structure and connecting them on a support plate will produce a splitter with very good parameters – more than doubled WR and a linear variation of the transmission, also doubled – from 27% to 99 %.

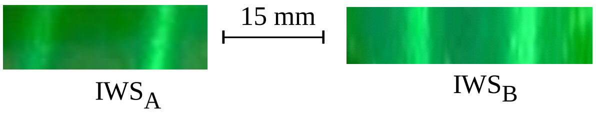


Figure 6. Two IWS (A and B) with equal parameters, except the composed mirrors reflectivity ($R_{A,B}$ = 0.75/0.6, $\alpha_{A,B} \approx$ 10 µrad, $e_{A,B} \approx$ 3.5 µm).The Fizeau lines are visualised by illumination with a green laser.

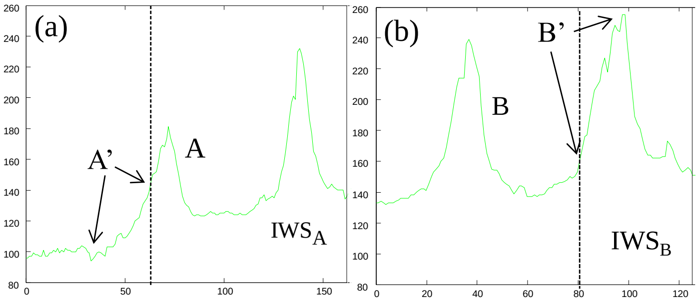


Figure 7. Scanned graphs of FL of two IWS with specially chosen parameters to be composed IWS with improved parameters as beam splitters. The selected parts are with part of FL A' and B'.

The experimental test of the proposed improved splitter is illustrated in figures 6 – 8. To produce practically beam splitters of joint two parts from different wedged interference structures with suitable characteristics, it can be used mask's technology, or cut and collect both parts. The two Fizeau wedged structures are with equal parameters

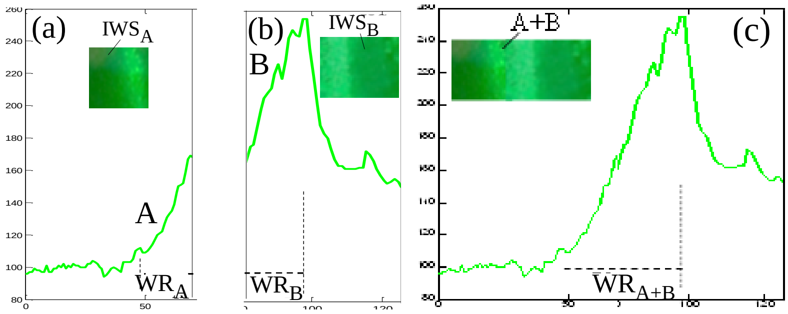


Figure 8. The selected parts of the IWS discussed already and composed beam splitter by them with improved splitting action

except reflectivity of the composing mirror ($R_{A,B}$ = 0.75/0.6, $\alpha_{A,B} \approx 10$ μrad, $e_{A,B} \approx 3.5$ μm). The parts of the structures IWS_A and IWS_B with visualized Fizeau Lines (FLs) by illuminating with green laser light (532 nm) are shown in figure 6. The scanning of these parts with their Fizeau lines are presented as graphs in figures 7(a) and 7(b). These structures correspond well to the idea to obtain FL splitting line that is with increased maximal and decreased minimal transmissions and more than two times widened WR compared to this one in single IWS. Formation of the beam splitting structure, taking the two parts A' and B' of the Fizeau lines with the corresponding parts of the structures, is illustrated in figures 6 - 8. In the figures are presented the selected parts from both described already structures with the corresponding parts from the Fizeau lines. The structure IWS_A (figure 7a) with high reflectivity mirrors, as can be seen from the scanned Fizeau lines, assures low minimal transmission (~ 10%) and, as a problem, also low maximal transmission (~50 %, the first FL). Contrary, the structure with low reflectivity mirrors IWS_B (figure 7b), assures maximal transmissivity (~ 1), but, as a problem, also high percentage of minimal transmissivity (~ 40%). The two parts of the lines A and B – respectively A' and B' in figure 7, which have near equal slopes, can be linked into one line with very suitable splitting characteristics as it is shown in figure 8. The combined line has minimal transmission of ~ 10%, maximal one ~ 95 % and has slope approximately two times lower than for the single line.

6. Conclusion

In this work, we proposed and demonstrated by theoretical analysis, simulation and experimental test the principle of implementing of interference wedged structure – a beam splitter with improved characteristics. The solution proposed shows useful potential – compactness, simple and precise controllable linear splitting, and conservation of the propagation direction of the formed beams.

Acknowledgements

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References

[1] Demtröder W 2008 *Laser Spectroscopy* (Springer, 4th ed.)
[2] Stoykova E and Nenchev M 2010 *J. Opt. Soc. Am.* **27** 58–68
[3] Nenchev M and Meyer Y 1981 *Appl.Phys.* **24** 7–9
[4] Stoykova E and Nenchev M 2001 *Aplied Optics* **40** 275402–11
[5] Nenchev M, Stoykova E and Deneva M 2018 *Optical and Quantum Electronics* **50**(12) 433
[6] Deneva M, Nenchev M and Stoykova E 2019 *Proc SPIE* **11047** 110471G
[7] Deneva M, Uzunova P, Kaimakanova N, Atanasov D, Ivanov N, Nenchev M and Stoykova E 2019 *IOP Confer. Series: Materials Science and Engineering* **618** 1 012016