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Competitive light wavelength division multiplexing element based on tunable interference wedged structures

Marin Nenchev*[a], Margarita Deneva[a], Elena Stoykova[b]
[a] Technical University –Sofia and Plovdiv Branch, R&D Dept., QOEL-Scientific Laboratory;Plovdiv, Bulgaria; [b] Institute of Optical Materials and Technologies, Bulgarian Academy of Sciences, Sofia, Bulgaria

ABSTRACT

Interference Wedged Structure (IWS) is an optical element with useful properties for optical metrology, spectral analysis and optical communications. We have introduced in the paper a new perspective element of this type – Composite Tunable Interference Wedged Structure (CTIWS). The CTIWS is list-like sequence of superimposed wedged layers each with reflecting surfaces. For conveniently chosen apex angles and thicknesses of the layers, the CTIWS can assure high spectral selectivity to 0.01nm within a spectral range of 10 nm and more at smooth tunability by simple sliding of the structure along the wedge arm (a few cm). We have developed simple physical description of the IWS and CTIWS by adapting Fabry-Perot theory. We show that for the most important practical cases the results are similar to the obtained by more complex exact analytical description. The theoretical predictions are confirmed by experimental results. On the base of IWS and CTIWS combined in a suitable architecture, we have introduced and studied a new lossless Wavelength Division Multiplexing (WDM) element with independent tuning of each output/input. We considered the WDM implementation for the case of fiber optical systems used in optical communications.

Keywords: interference, Fizeau wedge, composite tunable wedged interference structure, wavelength division multiplexing

1. INTRODUCTION

The Interference Wedged Structure (IWS)[1-5] is an optical element which is most frequently based on multiple beams interference. Until recently, the IWS slacked somehow popularity and found limited application as spectral analyzing elements. In our previous works, we have shown potential of these structures in laser technology as elements for laser spectral control. We found new properties of these structures that can be a basis for new applications as e.g. spectrally selective reflection in direction different from that given by Snell's law and asymmetry in transmission[3-6]. Recently, we have introduced and patented new structure of this type – a Composite Tunable Interference Wedged Structure (CTIWS) - in combination with its usage as an attractive Wavelength Division Multiplexing (WDM) element[9]. The IWSimplemented as composition of interferential wedges (IWs) makes possible achieving high selectivity (narrow resonances) in combination with large interval of spectral and spatial tuning[1]. The IW as a single gap wedged structure has several well-known drawbacks[1]. The light beam passing through an IW illuminated by spatially extended light beam consists of parallel lines - the so called Fizeau lines[1], which correspond to the spatial resonances. Existence of Fizeau lines limits the tuning of a small diameter light beam at sliding the IW within the distance separating Fizeau lines. Occurrence of Fizeau lines decreases strongly the free spatial range of the interferential structure to be only the distance between two lines. Also, the free spectral range is limited by repetitive appearance of spectral resonances, corresponding to a given thickness. The free spectral range decreases with the IW's thickness whereas the spectral resolution is improving at larger thickness. To increase the distance between the spatial and spectral resonances, a wedge with a very small apex angle and small thickness must be used[1]. However, in this case, both the spatial lines and the spectral widths of the resonances enlarge, and this is a strongly limiting factor for various applications. To obtain a narrow resonance at

* marnenchev@yahoo.com

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a large free range and a small spectral width, in our previous work [6] we introduced a system built from a pair of separate IWs – a thin and thick wedges – with no related parameters. The synchronized tuning of a coinciding spatial resonance for both wedges was made independently by synchronized mechanical sliding of each of the wedges, and this substantially complicated the device. Description of combined usage of two IWs for improvement of the spectral resolution exists in the literature, but without solution of the issue with the synchronized tuning[7]. Therefore, the first task of this paper is to propose solution of this issue based on a CTIWS (Figure 1). By using a simple model, we show that a two-angle CTIWS consisting of two separate wedged layers with suitably chosen parameters as gap thicknesses, apex angles and refractive indices can produce a single spatially and spectrally narrow resonance due to the thick wedged layer at large free distance ensured by the thin wedged layer. A single resonance at other wavelength can be achieved within this distance through sliding the CTIWS that causes wavelength tuning of the transmission.

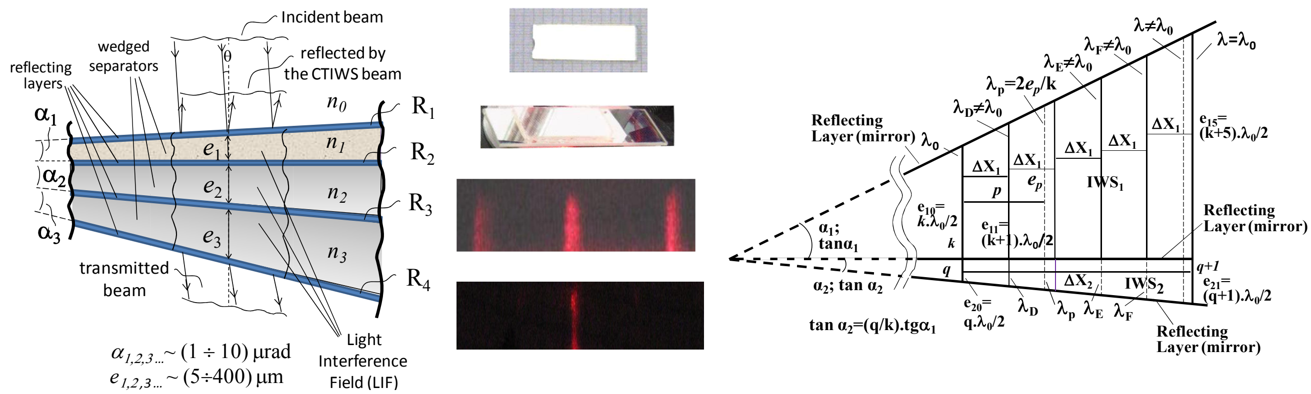
The WDM elements are of great importance for optical communications and laser technology. As a second task in the paper, we propose implementation of a competitive WDM element on the base of our patent [9] through sequential arrangement of CTIWSs (also IWs) in a proper architecture. More specifically, we describe in the paper properties of an IWS and a CTIWS that permit to connect the WDM element to an optical fiber system. As it is well known, the WDM elements are very important for the hardware of optical communications [10]. In the literature [8] there are presented few solutions based on prisms and diffraction gratings (generally with low dispersion – selectivity and relatively high losses), Fabry-Perot type filters with limited tunability of the outputs/inputs; important for real applications is the elements based on a Bragg grating, however, with complexity of tuning the outputs /inputs. All these elements have advantages and drawbacks, and this justifies research in this area. The proposed by us new WDM element demonstrates high selectivity (0.01 nm and less) with continuous tuning in a large spectral range (10 nm and higher), controlled separation of the needed power for each output and without useless losses; precise tuning of each output/input without cross-talk with the other output/inputs; simplicity in construction and very simple mechanical tuning (manually or electrically). This WDM element may find special applications for high power light beams with power densities (MW-GW)/cm^2 (no communications systems).

This work gives generalized presentation of a CTIWS, an IWS (with emphasis on an IW) and a WDM element by modeling, analysis and experimental verification and points out specific features of these structures. Firstly, we consider the CTIWS in comparison with the IW as a building component of optical devices. We propose as implified model for analysis and give experimental data proving useful properties of these elements from the point of view of their utilization in fiber systems. Secondly, as a consequence of the first task, we present a new WDM element as a principle, experimental implementation and potential for application in fiber systems (optical communications).

2. CTIWS – MODEL, ANALYSIS AND PROPERTIES

The proposed by us CTIWS is built from layered mirrors, separated by transparent wedged layers (gaps) with appropriate parameters – apex angles, refractive indices and thicknesses. Note that the IWS by definition possesses ideal plane boundary surfaces for each wedged layer (gap) and plane reflecting layers (mirrors). The CTIWS is a list-like element with typical dimensions 1 cm × 4 cm × 0.2 cm that can select a single narrow resonance. It transmits a spectral line of 0.01 nm or less at 30-70 % transmission that is tunable along the length of the structure. Tuning is performed by sliding the structure in its plane within a spectral interval of 10 – 100 nm. Generally, the CTIWS can act as a spatial wavelength analyzer with high spectral resolution when it is illuminated by a large diameter multi-wavelength beam. However, the main interest is applying the structure in the hardware of the optical communications and in laser technology and this requires high spectral and spatial resolution with tuning in a large free range of a small diameter light beam.

Schematic representation of a three-angle implementation of a CTIWS is shown in Figure 1. The structure contains three gaps. The simplest realization of an IWS (known as an IW or Fizeau Wedge[1]) is the case with a single separating wedged layer. The main properties of the IW are described in the literature, including also our previous publications[3-6,8]. To present adequately the CTIWS and WDM, we give brief description of some specific properties of the IW related to application in optical communications.



(a) (b) (c)

Figure 1. (a). Triangle variant of Composite TunableInterference Wedged Structure (CTIWS); e_i, n_i – thickness and refractive indices of the gaps, R_i – reflectivity of the layers-mirrors; (b): (top) a photograph of an IWS (layers deposited on a glass plate) and a two-angle CTIWS composed by two suitably chosen wedged structures, (bottom) transmitted light through a single IW(top) and through a CTIWS for expanded beam from He-Ne laser;(c): geometrical representation of a CTIWS composed by two single-angle IWS, cross-section with a plane perpendicular to the ridge.

We developed simplified model and mathematical description of the CTIWS action. In the simplified model the CTIWS can be considered as consisting of closely imposed IWSs (Figure 1c). In the general case with non-related values of the parameters of these IWSs, when the CTIWS with two, three and more gaps is illuminated, the structure does not transmit light in defined and controllable manner due to chaotic interference of the partial waves, formed by sequential reflections from the mirrors. For suitably chosen parameters, the CTIWS demonstrates specific useful properties.

Let us consider a CTIWS presented as two single-angle interference wedged structures IWS_1 and IWS_2 (Figure 1c) with the following parameters: 1) wedge angles α_1 and α_2; 2) refractive indices $n_{1,2}$; 3) wedges thicknesses $e_{1,2}$ and optical thicknesses $e^*_{1,2} = n_{1,2}e_{1,2}$ that correspond to the given point of the wedge. The wedge gap thicknesses increase or decrease linearly with the distances $X_{1,2}$ from the apex points as $e_{1,2} = X_{1,2}\tan\alpha_{1,2}$ .Note that we use $\tan\alpha_{1,2}$ instead of just $\alpha_{1,2}$ that is typically used in the literature in view of the small apex angles in the IWSs (1–100 µrad). It is convenient to choose the same current thickness for the wedges $e_{s1,s2}$ as initial thickness and to calculate the thicknesses $e_{a,b}$ at a given distance $p_{a,b}$ from this point on *X*. Thus we have $e_{a,b} = e_{sa,sb} + p_{a,b}\tan\alpha_{a,b}$. In the model (Figure 1c), the line *X* is in the wedge mirror plane, the line perpendicular to X is Y coordinate. Note that we can increase the scale along axis Y with factor of *M*, and the real value of the wavelength must be magnified with the same factor *M*.

We consider the IWS behavior from the point of view of selection of a narrow resonance with large tuning range by sliding the structure. When the wedge angles are very small being in most practical cases of the order of 10^{-5} rad, the IWS is practically completely plane. Typically, for applications in optical communications and laser technology, illumination is done by a small diameter beam with respect to the spatial resonances. Our model is based on the idea that the IW can be considered as a sequence of Fabry-Perot interferometers along the wedge arm with linearly variable thickness. Thus, the IW at each point can be considered as a small area FPI. Comparison with our experimental results and with typical cases of precise calculations performed following the technique developed in our works [2-4] shows that such a simplified analysis has acceptable precision for important practical cases. We use the following expression for the transmission from the general theory of FPI [1]:

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

where $\delta = \dfrac{4\pi}{\lambda} en\cos\theta_i$, *e* is the constant thicknesses of the FPI, *n* is the refractive index of the gap, $\cos\theta_1$ is the angle of the incident ray (beam) inside the gap, λ is the illuminating wavelength and *R* is the reflectivity of the FPI's mirrors. One may easily obtain the relation between the apex angles $\alpha_{1,2}$of the structures and $\Delta X_{1,2}$ as:

$$\tan\alpha_{1,2} = \frac{\lambda_0}{2n_{1,2}\Delta X_{1,2}} \qquad (2)$$

The geometrical thicknesses of $IW_{1,2}$ that vary linearly with the distance from the apex angle (along X axis) and respectively with distance p from the line of the chosen initial geometrical resonant thicknesses e_{10} and e_{20} are given by

$$e_1(p) = e_{10} + p\tan\alpha_1 \qquad (3)$$

$$e_2(p) = e_{20} + p\tan\alpha_2 \qquad (4)$$

For wavelengths λ_1 and λ_2, corresponding to the thicknesses given by (3) and (4), after some analytical transformations, we obtain:

$$k(\lambda_1/2) = (e_{10} + p\tan\alpha_1)n_1\cos\theta_{i1} \qquad (5)$$

$$q(\lambda_2/2) = (e_{20} + p\tan\alpha_2)n_2\cos\theta_{i2} \qquad (6)$$

where k and q are integers. From the expressions (5) and (6), taking into account that $2e_{10}/k = \lambda_{10}$ and $2e_{20}/q = \lambda_{20}$ $2e_{20}/q = \lambda_{20}$ we can obtain variation of λ_1 and λ_2 with p as :

$$\lambda_{1,2} = \lambda_0\left(1 + \frac{p\tan\alpha_{1,2}}{e_{10,20}}\right) \qquad (7)$$

From Eq.(7), the condition for equally selected wavelengths ($\lambda_1 = \lambda_2 = \lambda_c$) for the given p and respectively for wavelength tuning by sliding the CTIWS's is:

$$\frac{\tan\alpha_1}{e_{10}} = \frac{\tan\alpha_2}{e_{20}} \qquad (8)$$

and in view of Eq.(1) we obtain the general formula for selection of a single resonance and continuous tuning by sliding

$$\frac{n_1}{n_2}\frac{e_{10}}{e_{20}}\frac{\cos\theta_{i1}}{\cos\theta_{i2}}\frac{\Delta X_1}{\Delta X_2} = 1 \qquad (9)$$

Expressed through the optical thicknesses, the condition for equal tuning of λ can be written as:

$$\frac{n_1\tan\alpha_1}{e^*_{10}} = \frac{n_2\tan\alpha_2}{e^*_{20}} \qquad (10)$$

and the expression for the commonly tuned λ as

$$\lambda = \lambda_0\left(1 + \frac{pn_{1,2}\tan\alpha_{1,2}}{e^*_{10,20}}\right) \qquad (11)$$

As a numerical example let's consider a two-angle CTIWS similar to those used in practice. It is built as combination of a pair of reflecting layers-intermediate gaps (as given in Figure 2). The parameters of the first IWS_1 area follow: $e_1 = 20$ μm, $\alpha_1 = 5\times10^{-5}$ rad, and for the second IWS_2 they are $e_2 = 5$μm, $\alpha_2 = 1.2\times10^{-5}$ rad; the refractive indices are $n_1 = n_2 = 1.5$ with reflectivity of the mirrors $R_i = 85\%$ and the beam incidence angle $\theta_i \sim 0$ at wavelength 0.6328 μm (He-Ne laser). This parameters are chosen to be approximately equal to the parameters of two specially selected our structures. These two structures are superimposed by pressing the rear dielectric layer (mirror) of the first structure to the front layer of the second. This permits us to study properties of the two structures separately and in the CTIWS. We have observed that precise superposition of the two dielectric layers (mirrors) results in their acting as one mirror with nearly the same reflectivity as reflectivity of a single mirror. The parameters of the two single-angle structures that compose the two-angle structure satisfy Eqs. (8) and (9).The results of computation using Eqs. (9) and (10) are presented below in Figure 2 (left) and the photographs of the observed transmission are shown in the middle.

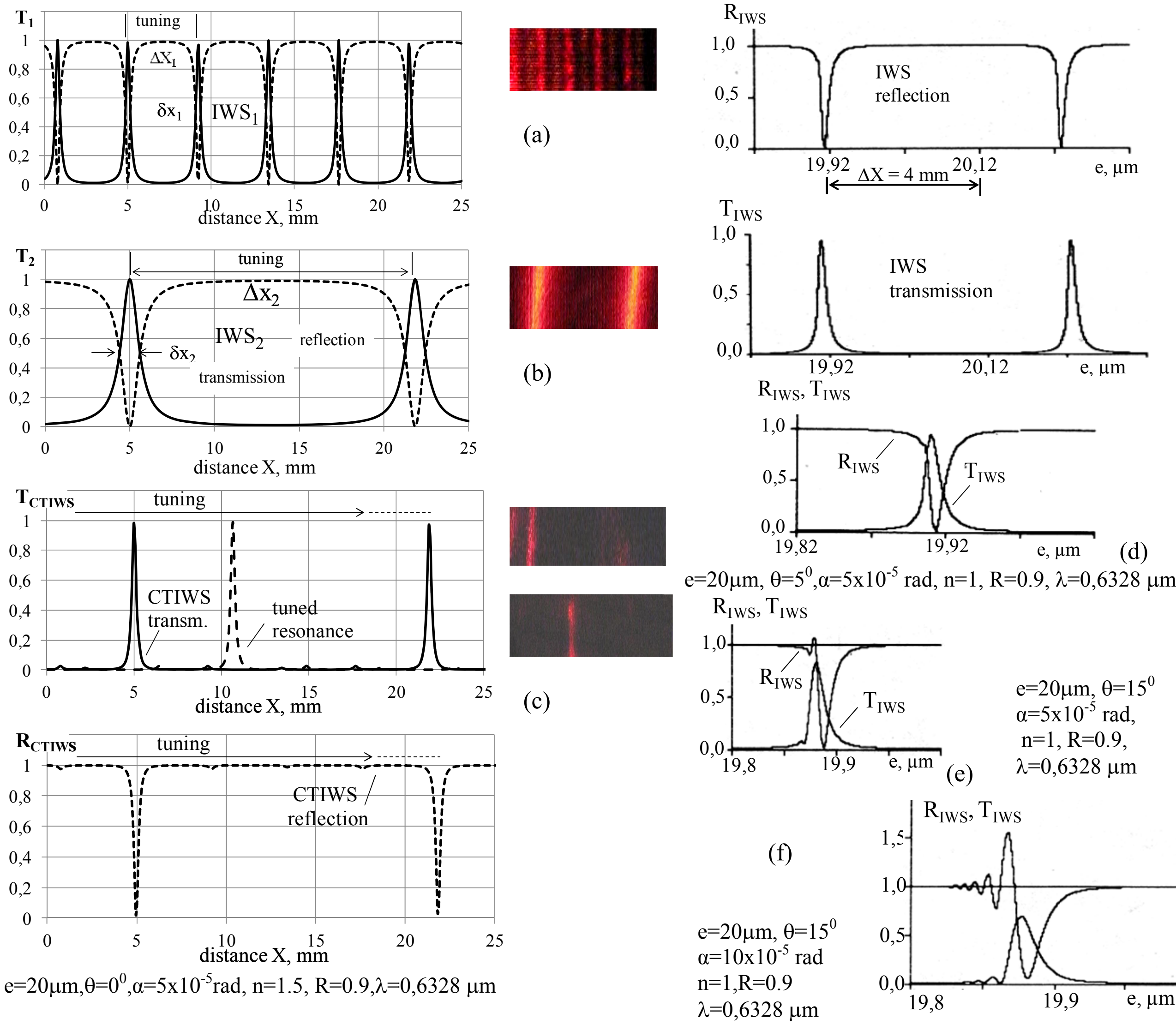


Figure 2.(a, b c) – *left*: Computed transmission T and reflection R and selection of the CTIWS using approximation with continuesly variable thickness FPI: *top*, a – for the tick IWS_1, *middle*, b – for the thin IWS_2 and *bottom*, c – for combining the two structures in one two-angle CTIWS. (a, b, c) - *middle*: corresponding photos of experimental realization of the IWSs, (d, e, f) – Graphs of exact calculations with almost the same parameters as those for CTIWS: (d) - three graphs for the thickness and wedge angle corresponding to the CIWS, (e) and (f) – the resonances for different angles and thicknesses. The values of the parameters and discussions are given in the text.

Coincidence of the selection of the two structures and synchronous tuning of the two selected wavelengths can be seen (the graph noted as "tuned resonance", calculated for randomly chosen thickness of the CTIWS in the tuning range). Strongly (4 times) enlarged tuning range in combination with essential spectral (~ 5 times) and spatial (~3 times) narrowing of the selection is achieved. The linewidth of the selected line for the given parameters of the composed structure can be calculated to be ~ 0.4 nm (given by the thick IWS_1). It can decrease to 0.2-0.1 nm if we increase the reflectivity of the layers-mirror to 0.9-0.95. The spectral tuning range is 2×6.7 =13.4 nm (given by the thin IWS_2). Theoretical transmission is equal to 1 whereas the real one depends essentially on the quality of the layer - absorption in the mirror and wedged layers. We measured experimentally maximum ~ 50% transmission. For high quality layers the losses must drop drastically, theoretically approaching 0. The strong decrease of the linewidth can be achieved using combination with thicker wedge gap for IWS_1, i.e. 80-100 μm that leads to 0.05 nm; the tuning range is about 3 nm.

The experimental data confirm the theoretical estimation. Combining the two structures with very close parameters to those in calculations (19.4 μm, 5.10^{-5} rad; 4.8 μm, 1.2×10^{-5} rad and R~ 85 %), we have obtained results similar to calculation (except the transmission which was, due to quality factors of the layers, about 50%). Essential issue is comparisons between the results of exact theory of IWS and CTIWS, that are obtained by approaches developed by us in [2,3,4] and the approximation derived from FPI theory with linearly variable thickness of the FPI. We checked theoretically the correctness on the base of comparison of the results for a single angle IWS with parameters close to the already given in calculation for the case of FPI theory adaptation. The illustrating results for some of the parameters are plotted in Figure 2 (d, e, f).

In general, from the theoretical analysis and experimental results we conclude that descriptions of IWS and in particular CTIWS by the approximation of a FPI with continuously variable thickness and by the exact theory are comparable for relatively small range of thicknesses (2-100 μm) , wedge angles (1 – 100 μrad), incident angle less than 15^{o}, and mirror reflectivity ~70-90%.

3. WDM ELEMENT BASED ON IWS AND CTIWS AND COUPLING WITH AN OPTICAL FIBER SYSTEM

Following the theoretical and experimental results in Sec.2, it is clear that under illumination with a multi-wavelength small diameter beam the IWS and CTIWS transmit only light at the wavelength, corresponding to the structure transmission resonance for the point of incidence. The action of the CTIWS as high spectral and spatial selective list-like element, tunable by sliding in its plane, is illustrated schematically in Figure 3, where the left part of the figure elucidates the principle as well as the right part experimental performance. The photographs show the transmission at two different wavelengths (red light - left and yellow light - right, He-Ne laser) at two different incident points of the beam on the structure obtained by sliding in its plane (these wavelengths have been chosen for better visualization).

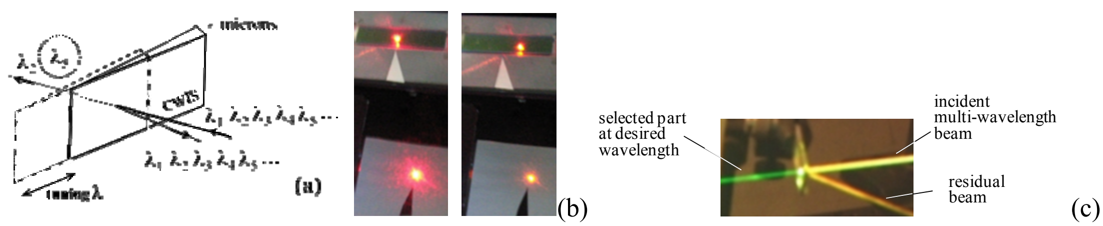
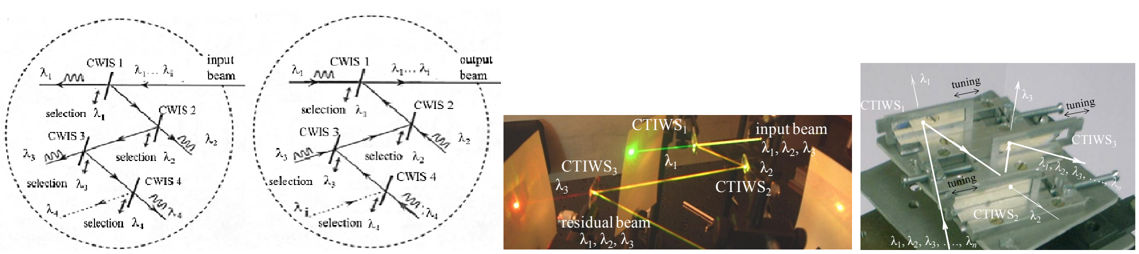


Figure 3. Schematic of the desired wavelength separation from the incident beam by sliding the structure (a) and photographs of real action (b); (c) photograph of separation of a part of the incident beam at the desired wavelength.

The typical transmission of the two-angle CTIWS varies from 10% to 70% depending on the parameters chosen for the specific task as e.g. achieving very high selectivity (width of the line is a part of nm, spatial width is a part of mm) or operation as a pre-selector (linewidth about one nm). For high quality layers, the theory gives that sum of the transmission and reflection is 1. The non-transmitted light is reflected, as it is shown in Figure 3 (c).



(a) (b)

Figure 4. (a) Schematic realization of WDM element on the base of parallel architectures with CTIWS or IWS as a wavelength (channel) separator and as a multiplexing element. For the incident multi-wavelength beam (input beam – *left* picture) any structure selects the desired wavelength. The selection by sliding the list-like structure does not change the propagation direction of the reflected beam and respectively does not disturb the selection of other structures (channels); (b) Demonstration of WDM set-up in action-*left* and initial compact model of working prototype–*right*

The properties of the IWS, arrangement as a list-like element and tuning by sliding permit development [6] of original solution of a WDM element-structure. The principle of its realization is shown in Figure 4. It consists of series of parallel CTIWSs which reflect the input beam from one to another. The tuning of each input-output, performed by sliding the plane structure, does not disturb selection of the other input/outputs. The output power at the selected wavelength is extracted from the incident beam by simple deviation of the incident point from the exact position of the resonance. The element works theoretically without energy loss.

Important possibility offers the observed by us feature of the IWS, including the CTIWS, to work well under illumination with a light beam focused by a short focal length lens ($f \sim$ 2-5 mm). The focal spot is ~0.2 mm and for structures with thicknesses of 5μm – 30μm, angles ~2-10 μrad, R~85-90%, transmission at the resonant point reaches more than 80%.

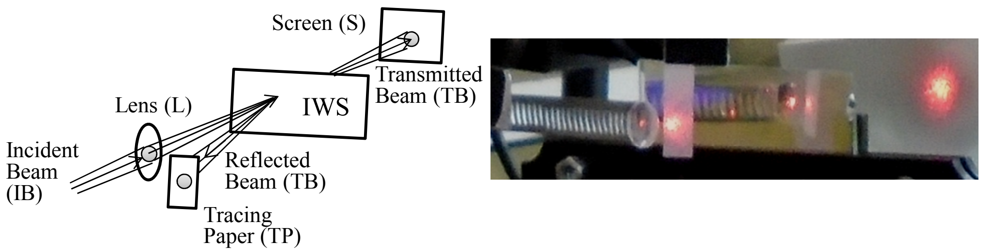


Figure 5**.** Transmission of the beam focused with a short focal length lens (2 mm) through an IWS. *Left* – schematic presentation, *right* – real photograph. The spots of transmitted (on tracing paper TB) and reflected light (on tracing paper TP) are shown.

Another interesting feature is observed when the discussed wedged structures IWS and CTIWS are illuminated by a fiber (aperture ~ 100μm) closely placed to their surface normally or at small angle up to 15^o. The structures shows good performance with resonances for the illuminating fiber output light beam that correspond well to the distance for illumination with a narrow collimated beam. The experiment was done with a He-Ne laser. The experimental set-up is shown in Figure 5, where illumination with symmetric near Gaussian beam by closely disposed 100 μm fiber with red He-Ne laser light can be seen. The divergence is estimated to be ~ 1.2^o. The parameters of the single-angle IWS are e=5 μm,$\theta=0^0$,$\alpha=1.2\times10^{-5}$rad, n=1.5, R=0.8 and λ=0.6328 μm. It can be seen from the graph in Figure 6 that transmission of the structure is high approaching maximal for the mentioned divergence of the beam.

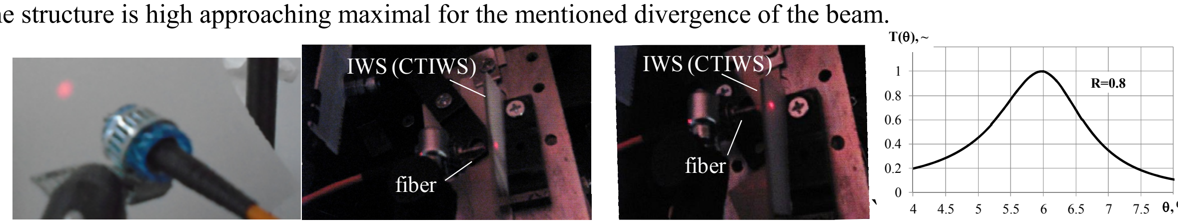
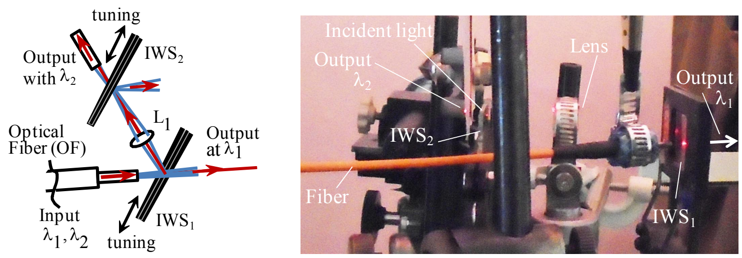


Figure 6. Transmission of the light, emitted by ~100 μm fiber by the IW-structure. Left – output beam from the fiber. Middle – transmitted through IWS light is visualized by plotted tracing paper on the back side of the IWS.Right –calculated transmission of the IWS for beam with near homogeneous intensity distribution (IWS with e ~5 μm, He-Ne laser).

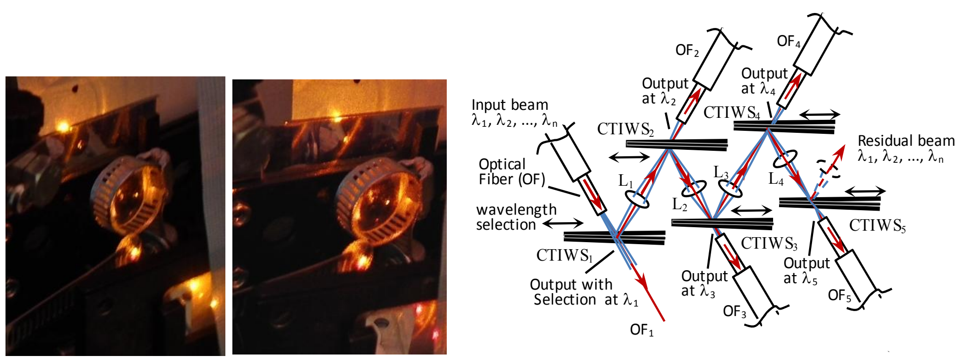
These two observations offer possibility to create a promising WDM element in fiber-short focal lenses arrangement. The schematic of the basic component of the solution that is multiplied in the new WDM-element coupled to a fiber-lenses system is given in Figure 7(a). Its practical realization as a laboratory model can be seen from the photograph in Figure 7(b). As it is shown in the figure, the end of the fiber with multi-wavelength light output is disposed closely at 5-10 mm from the first IWS_1 (similar to the one, described in Figure 6) and at small angle ~ 5^o with respect to the normal in the point of illumination. Part of incident light at the wavelength, given by the transmission resonance in the incident point, passes, the other part and the light at the other wavelengths in the complex beam are reflected toward the next structures. From the reflected beam, focused by the lens L on the second IWS_2 light is selected at the wavelength given by the resonance on which is adjusted the second IWS. The connection between IWS_1 and IWS_2 can be realized by the intermediate fiber (for long distance) in which, by the lens L, is introduced the focalized reflected light from IWS_1 and with repetition of the discussed already action of the arrangement. The IWS_1 and IWS_2 can be implemented as one-angle wedged structures (type IW) as well as CTIWS with two or three angles. The principle and the action are the same for all mentioned cases. The advantage when the CTIWS is used is that the selectivity and the tuning range increase essentially. With a simple IW one can select light of spectral width of the order of a few nanometers going down to part of a nanometer (5-1-0.5 nm) tunable in the range of few nm. Use of a CTIWS permits to obtain a linewidth less than 0.05 -0.01 nanometers combined with tuning within ~ 10 and more nanometers.



(a) (b)

Figure 7. (a) The schematic of the basic component of the solution that is multiplied in the new WDM-element, coupled in fiber-lenses system. (b) Practical realization as laboratory model - photograph.

The photographs in Figure 8(a) illustrate the independent tuning of the outputs of the presented in Figure 7(a) experimental WDM implementation based on the fiber-lens – IWS. The tuning is achieved by sliding the IWS_1. The first output changes the wavelength, and as it can be seen, the second is not influenced. The generalized schematic of the fiber-lenses WDM element as composed from components schematically presented in Figure 7 is given in Figure 8.



(a) (b) (c)

Figure 8. (a,b) Photographs of demonstration of the action of laboratory arrangement - model of the fiber-lenses-IWS WDM system with two IWSs. By sliding the first IWS, the output is tuned, the other output remains at the same wavelength. (c) Generalized schematic of the WDM element composed from fiber-lenses-IWSs as multiplication of the component in Figure 7.

4. CONCLUSION

In summary, we have studied the unique properties of the proposed by us Composite Tunable Interference Structures (CTIWS). In parallel, we have considered some new aspects of the Interference Wedged Structure (IWS) and the CTIWS behavior in interaction with fiber transmitted light which is great interest for optical communications. We have shown the possibility to develop WDM-type system on the base of IWS and CTIWS that has useful competitive properties – high selectivity in large spectral range, independent spectral selection (i.e. channel's tuning) of each output-input, without disturbing the other channels, potential for low useless energetically losses in the WDM devices. We have proposed a simplified approach for analysis of the discussed wedged structures on the base of Fabry-Perot theory and have shown it applicability for evaluation the parameters of the IWS and CTIWS. The analysis shows that CTIWS can assure selection of single narrow resonance, i.e. selection of a spectral line (~0.01 nm or less), tunable along the length of the structure by simple translation in its plane (i.e. sliding; spectral interval of 10 – 50 nm).The structure represents a list-like tunable filter (dimensions ~ 1 cm × 4 cm × 0.2 cm). The essential progress achieved in the present work concerning the potential the CTIWS and IWS is related to the progress of technology of very high quality dielectric layers – building components for discussed structure (nano-flatness, very low loses material for producing the layers).

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