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Combined implementation of controllable beam splitting and wavelength division multiplexing using tunable interference wedged structures

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ABSTRACT

The focus of the work is on development and implementation of competitive optical elements based on tunable interference wedged structures. Such a structure can be a single interference wedge (two reflecting surfaces separated by a gap with increasing thickness) or a composition of two or more superimposed wedged layers with adjusted parameters. We used these structures to build a new wavelength division multiplexing (WDM) element and realized coupling of these elements with a fiber optical system as an issue of essential interest for optical communications. Under illumination with a multi-wavelengths beam, the composed WDM structure in the fiber system provides precisely controllable wavelength selection (resolution better than 0.01 nm) within the range of more than 15 nm and with controlled continuously variable transitivity from 1-3 to 80 %. The non-transmitted power with the other non-selected and completely reflected light is directed to the next output (theoretical loss of the system ~ 5 %). The WDM-structure works at completely independent spectral selection of each output/input without any influence between the tuning of the channels.

Keywords: beam splitting; WDM, wedged interference structure, optical fiber communications.

1. INTRODUCTION

The Wavelength Division-Multiplexing (WDM) elements and devices are important components of the hardware base in optical communications and quantum electronics, for example in multi-wavelength lasers. As is described in the specialized literature[1-3], such elements can use the dispersion produced by gratings and prisms, including Bragg structures, or can be based on spectrally selective layers or holographic effects. Based on our experience gained in the field of the interference wedged structure (IWS)[4-7], we have recently introduced a simple and effective technique for a multi-wavelength division-multiplexing, that relies on utilization of optical wedges with reflective coatings. The optical behavior demonstrated by the IWS makes possible building of a WDM element with useful and competitive properties. This motivates the research for further development and improvement of these elements. Their main advantages are as follows: i) easy operation with many spectral ports (outputs-inputs) at high selectivity of the order of 0.01 nm and less in the spectral range of 10-15 nm; ii) completely independent tuning of each port without disturbing the selections in the other ports, iii) easy power selection control for each port, iv) operation with practically only useful losses, v) compactness and low price. The WDM device can work as a pre-selector for separation of different color lights at high spectral resolution. In our previous works we have presented the results showing the potential of the new WDM elements for the case of illumination with a collimated laser beams[7].

In the present work we report the development of a WDM structure, based also on an IWS, but for illumination by a laser beam emitted from a fiber and focused on the IWS. The objective of such research is enabling creation of multi-port WDM structures for optical fiber communications with long distance between the ports at keeping all advantageous features of the IWS-based WDM elements. For the purpose, we studied the IWS optical behavior for a focused beam,

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especially for a beam emitted by an optical fiber, and for the direct entrance of the beam, emitted by a closely disposed optical fiber. The advantage is also that the proposed WDM element, except the wavelength multiplexing and demultiplexing, can perform a beam splitting function at a controllable ratio between the transmitted and reflected power.

2. WDM ELEMENT BASED ON INTERFERENCE WEDGED STRUCTURE

2.1. Interference wedged structure

The proposed WDM elements exploit the properties of an IWS. The name of this structure is chosen to indicate that it can be implemented as a single optical wedge or a combination of several optical wedges. The simplest implementation of the IWS as a single wedge is known as Fizeau Wedge or Interference Wedge (IW) [4,8,9]. Recently we introduced a Composite Tunable Interference Wedged Structure (CTIWS [7]) built from a stack of optical wedges. The CTIWS is also an example of an IWS. A WDM element based on the IWS utilization requires adjustment of the parameters of the optical wedges as well as their specific arrangement in the IWS. For this reason, we briefly present some aspects of the IWS's optical behavior that have been established by us earlier in order to elucidate the principle of creating the WDM element.

A single-gap IWS consists of two flat partially reflecting surfaces inclined at a very small angle (10^{-5} – 10^{-6} rad) with respect to each other and a transparent gap between them of thickness tens or hundreds of micrometers. The gap may be air, a glass or other solid transparent material (Figure 1a). The most interesting for practice are the IWSs, which are built by transparent dielectric layers with reflective sides superimposed on the transparent support of glass, quartz or sapphire. The fringe pattern in reflection and transmission that is formed by a single-gap wedge under illumination by spatially and temporarily coherent light is determined by the apex angle, reflectivity of the surface coatings and refractive index of the layer between them. A monochromatic plane wave produces a sequence of transmission peaks, which are called Fizeau lines. The spatial distance between the Fizeau lines[8] is given by the wedge angle, α, and the wavelength of the illuminating light, λ, as $\Delta X = 0.5\alpha/\lambda$ for an air-gap wedge. The location of the resonant line is given by the resonance condition $k.\lambda/2 = e.n.\cos\theta$, where e and θ are the wedge thickness and the incidence angle of the light beam and k is an integer $k = 1,2,\ldots$ By varying the wavelength the peak location is shifted linearly along the wedge surface. This property enables the IW usage for spectral analysis of wide collimated beams. The thickness of the wedge affects the resonant conditions by decreasing the free spectral range of the IW and improving the spectral resolution at a larger thickness and at a given distance between Fizeau lines. The wide spectral range of a thin IW and the high spatial resolution of a thick wedge can be used by combining the wedges to form a CTIWS at properly chosen apex angles and thicknesses which guarantees coincidence of a single transmission peak in the sequences of Fizeau lines along their rear surfaces.

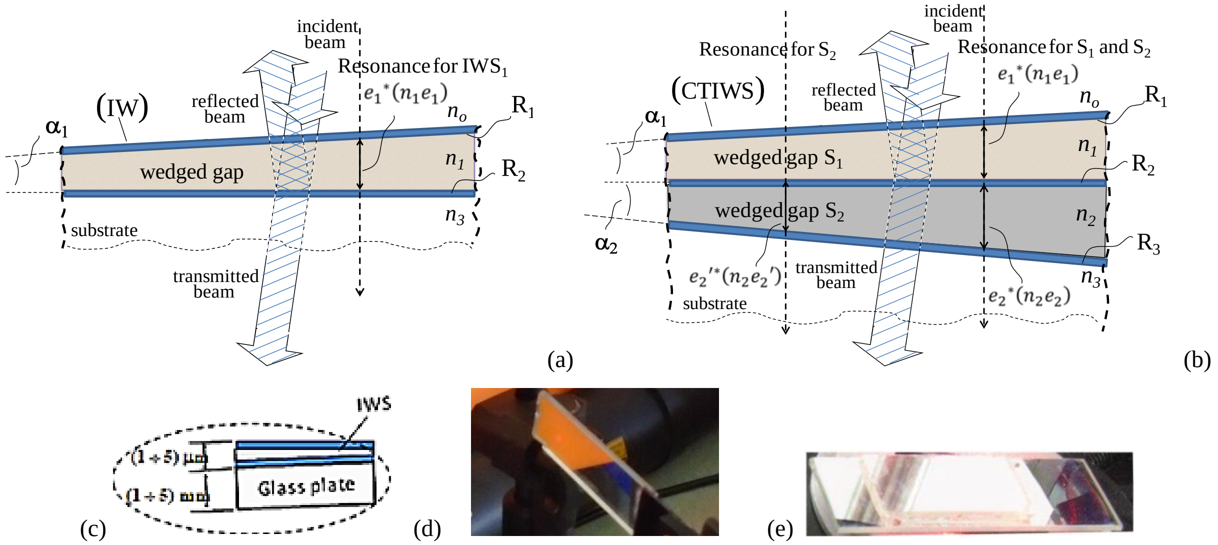


Figure1. (a,b) The schematic representation of a single-wedged gap and two wedged gaps IWSs; (c) schematic of the construction and (d, e) photogrphs of single gap-layer and two gaps- layer structures

If the diameter of the illuminating beam is smaller than the distance between the two resonance lines, and the beam falls in the vicinity of the spatial resonance on the wedge surface, the beam is transmitted at variable transmission. The transmitted power, which can be found by integration of the transmitted intensity distribution on the rear wedge surface, reaches maximum at the resonance and decreases when moving away from the resonant location. One may calculate the curve of the transmitted power as a function of the wedge thickness. Note that the resonant distribution of the transmitted intensity at given wedge parameters and the diameter of the incident beam is invariable with the wedge thickness. However, the width of the power curve, which is symmetrical with respect to the resonant point, decreases with the wedge thickness. The width of the transmitted power curve increases at lower reflectivity. If the illuminating beam is out of the resonance, the IW has low transmission. Thus, at a different wavelength the IW has higher or lower transmission depending on the place of incidence. A sliding of the IW can change linearly the wavelength of the maximal transmission for a fixed incident beam impact area, the latter being very useful property of the IW. The IW finds applications in spectral analysis[8], laser technology[3,7], and optical metrology[8].

Recently, we have developed a CTIWS[7] as another type of the IWS. The CTIWS, which is schematically depicted in Figure 1(b), represents properly superimposed wedge layers with suitably chosen parameters. The CTIWS has similar properties as the IW, however, it is characterized with an increased free spatial and spectral range of tuning with additional narrowing of the selected line[7]. It can be realized by the wedged gap-layers deposited on a single glass support or by deposition of each layer on a different support with superposition of these supports and respectively the layers. Figure 1(c) shows schematically the construction of an IW while Figure 1(d) and Figure 1(e) present the photographs of the typical IW and CTIWS respectively. As an important application of the IW and the CTIWS we have demonstrated a multi-output-input competitive WDM element with independent wavelength selection of each input–output and very convenient characteristics as potentially useful for applications in optical communications[10].

2.2. WDM element

In the previous works we proved the principle of operation of a WDM element built from IWSs for illumination with collimated incident beams. Photographs showing the IW action under illumination by a narrow collimated laser beam are given in Figure 2 (a) and (b). The power of the incident beam is divided between the transmitted and reflected beams as it can be seen in the figures. The illumination is by a collimated beam with nearly Gaussian intensity distribution at Gaussian diameter ~ 1.5 mm from He-Ne laser (at λ=0.6328 μm). The formed resonance line can be seen in the transmitted light on the screen. The top photograph shows the case of the illuminating beam outside the resonance (straight line) and the bottom – when the incident beam is in the resonance.

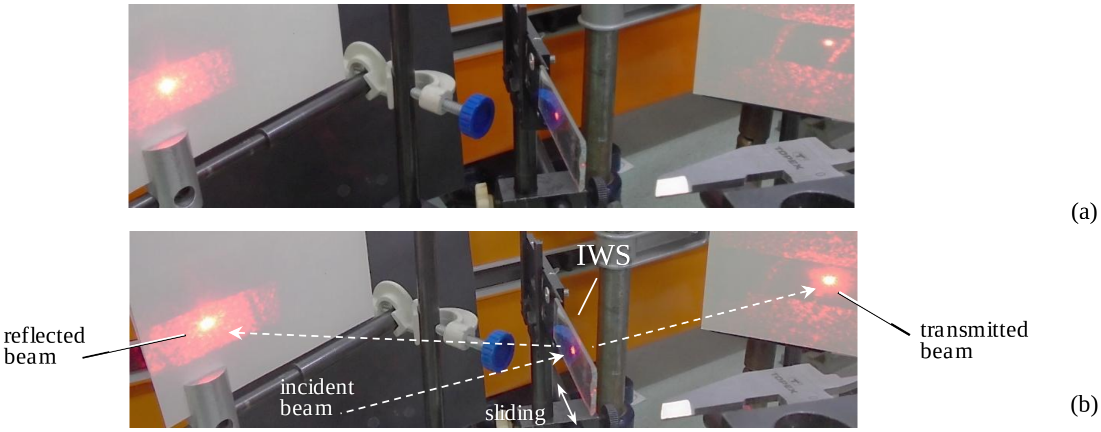
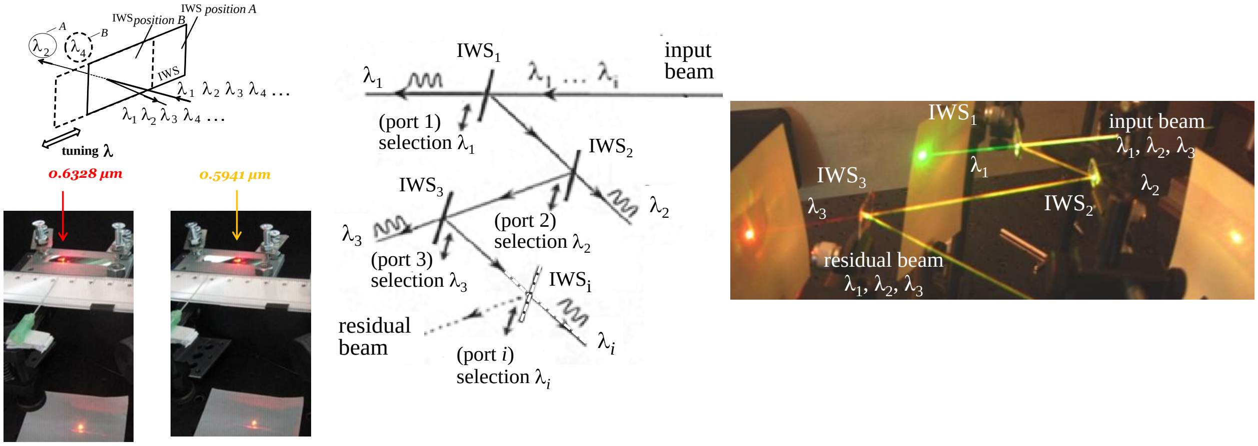


Figure 2. (a,b) photographs illustrating the IW action when it is illuminated by a narrow collimated laser beam. The power of the incident beam is divided between the transmitted and reflected beams as it can be seen in the figures.

Note that for different wavelengths the resonance condition is fulfilled for different products of the thickness and the refraction index, i.e. at different positions on the x-line (if *e.n* is 5 μm and cos $\theta \approx 1$, for λ= 0.6328 μm, k=16 we have *e.n* = 5.062 μm. For λ= 0.532 μm, k=19, *e.n* = 5.054 μm and for λ= 0.405 μm, k = 20, *e.n* = 4.938 μm). At some particular wavelength, the position can coincide for different values of *k*. The distance between two resonances is given as their thicknesses difference divided by the wedge angle. Thus, sliding the IWS in its plane at a constant direction of the incident beam, we change the resonant thickness *e.n* and respectively the wavelength of transmission that is important property for applications of IWS (Figure 3a). Of importance is also that the sliding is performed for the IWS that is plane, sheet-like element (Figure 3a) and there is no change of the direction of the incident, reflected and transmitted beams. In addition, for a given wavelength, around the corresponding resonance, the transmission varies with sliding of the IWS and thus permitting control of transmitted power. Taking into account the described properties of IWSs, we have proposed the multi output/input WDM element.

Below we describe shortly the principle of the proposed by us WDM element that is based on IWS application and its action in the case of previously considered collimated incident laser beam. Based on the already described properties of the IWS, the action of the WDM element composed from sequences of parallel IWS structures can be understood from the scheme plotted in Figure 3(b). The case of wavelength selection from the incident multi-wavelength collimated beam is shown. The flat IWSs are arranged in parallel in such a way that the input beam is sequentially reflected by any IWS. Each IWS is arranged to select the desired wavelength (communication channel). The tuning of the selected wavelength for a given IWS is done by its sliding and thus does not cause change of the beam propagation inside the arrangement of the IWSs. Respectively, the selected wavelengths for other IWSs (other ports) are not disturbed. In addition, by sliding the IWS around the resonance line for the selected wavelength, one can vary the IWS transmission for the chosen wavelength. The laboratory working model of the WDM system with linear beam is shown in Figure 3(c), where for demonstration the system acts with three color laser beams. Investigations performed with this model and other compact models confirm the expected advantages of the system.



(a) (b) (c)

Figure 3. Schematic of IWS as a flat sheet-like spectrally selective element, tunable by sliding (a); scheme of the WDM element composed as a sequence of parallel IWSs – wavelength division case with incident spatially narrow collimated beam (b) and laboratory working model (c).

3. WDM ARRANGEMENT WITH MANY IWS, LENSES AND FIBERS

3.1. IWS operation with a focused beam

The proposed new WDM system is an arrangement of tunable IWS (IW or CTIWS) and of optical fibers and lenses. The main advantage is the option this system to be used by many customers at long distance from each other (hundred meters or kilometers).

In our experimental work with the IWS, we have observed that optical properties of the IWS illuminated at a small angle (5-15 angular degrees) by focused laser light or by closely disposed to its surface optical fiber is similar to the properties obtained under illumination with a narrow collimated laser beam. The same resonances occur at the same location. This behavior is strongly expressed for the structures with thicknesses of 1-500 μm and a short focal length lens (2 – 7 cm).

The work of the IWS (case of IW) with a focused laser beam is illustrated in Figure 4. A He-Ne laser emits a collimated beam at 0.6328 μm with practically Gaussian intensity distribution with Gaussian diameter 2*w* of 1.5 mm. The beam is focused on the surface of the IW with an optical thickness 3 μm, reflectivity of the coatings $R_1=R_2=0.8$ and apex angle $\alpha=1.2\text{x}10^{-5}$ rad by a lens with 2 cm focal distance. The left picture shows the incidence at the resonance of the IW and the right – outside the resonance. The incident angle of the axis of the illuminating beam is $\theta\approx 10^{o}$ on the IWS front surface. The typical maximum transmission in the resonance for used IW with not so high quality layers and the Fresnel's losses in the walls of the supports is about 70 % (for some our samples of IW it reaches 85% with the losses in the layer ~ 5 %; theoretically the losses can be less than few percents[10]. The transmission for the beam completely outside the resonance, for the reflectivity of the wedge side walls of 80%, is ~ 1 %. The transmission can be continuously varied between the maximal and minimal values by sliding the wedge[11]. The action of the IW with focused beam for the treated case is similar to the case of illumination with the collimated beam. Actually, the focused Gaussian beam with diameter of ~0.1 mm and for the length of 10 - 100 μm (wedge thickness) near the beam waist has Rayleigh length ~ 5 m and a wave radius of curvature of ~ 25 - to 250 m. For the IWS with noted thicknesses practically the beam is plane wave with neglecting divergence that leads to the described IWS behavior. The experiments performed under illumination with a focused beam with Gaussian, near Gaussian and near homogeneous intensity distribution confirm the observed IWS action as for the small diameter of 1-2 mm beams. This proves gives the option of using the IWS in combination with lenses and fibers. The experimental example of such action is shown in Figure 4.

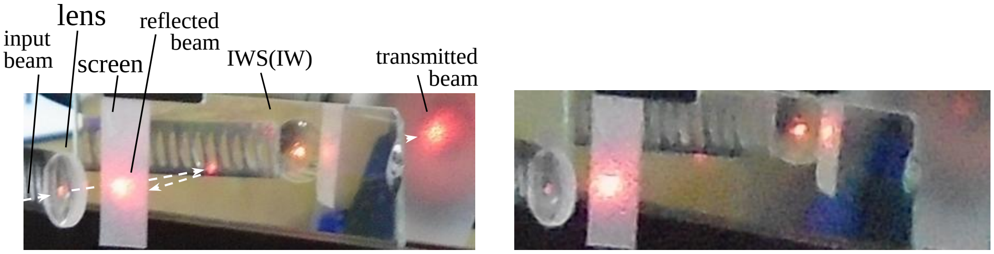


Figure 4. Transmission and reflectionof of focused laser beam on IWS (case of IW). A collimated beam at 0.6328 μm with practically Gaussian intensity distribution (2*w* of 1.5 mm) is focused on the surface of the IW with an optical thickness 3 μm, reflectivity of the coatings $R_1=R_2=0.8$ and apex angle $\alpha=1.2\times10^{-5}$ rad by a lens with 2 cm focal distance. The left picture shows the incidence at the resonance of the IW and the right – outside the resonance. The incident angle of the axis of the illuminating beam is $\theta\approx10^o$ on the IWS front surface.

The precise theoretical treatment of the transmission for IWS is relatively complicated, especially concerning the combinations of such structures [4,5]. As we have shown[10] there are possibilities for simplifying of the IWS treatment and combination of such structure with acceptable for practical evaluation precision. We have developed a simplified model on the base of Fabry-Perot Interferometer theory[8]. The basic idea is to consider IWS as consisting of a sequence of Fabry-Perot interferometers with a linearly increasing (or decreasing) thickness located close each to other along the line (line **x**) perpendicular to the wedge's apex.

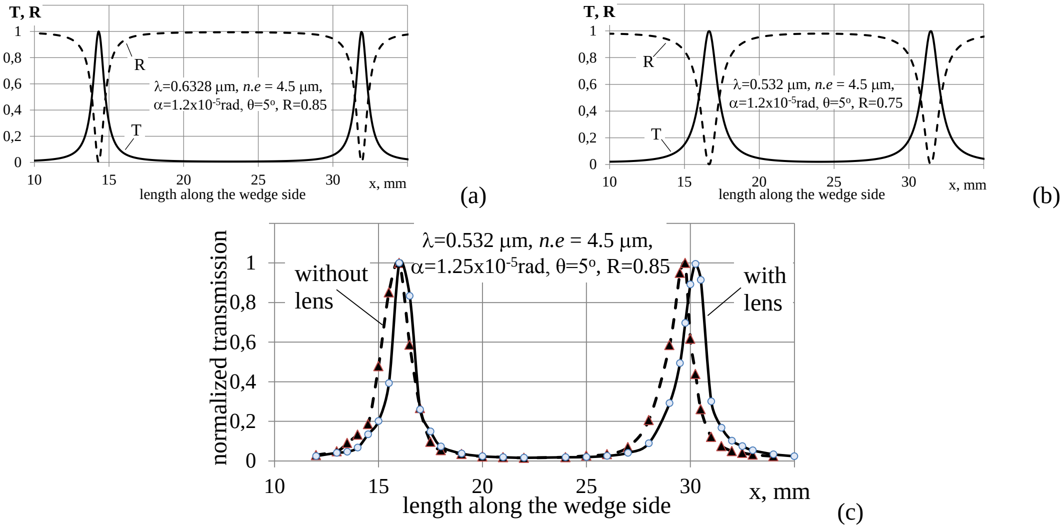


Figure 5. The computed theoretical curves of IW transmission T (solide line) and reflection R (droped line) for the incident narrow beam (a,b) and the graphs from the experiment for the case of incident of narrow paralel beam (solid line) and focused beam – dropped line (c). The point on the graphs in Figure 5(c) are from the experiments. The scales is equal. The IW parameters in analisysis in (b) and (c) are taken equal for comparision. The equal behaivior of IW for paralel and focused inciden beam (Figure 5c), permits to use a symplified theory for analysis of case with focused beam.

The results for particular cases, obtained both using the discussed approach and exact theory of IWS[4,12] and by the experiment, show that this approach can be used with acceptable precision for evaluation in practical interesting cases[10]. The approach is convenient for IWS's – single and composed pairs of it, which are with relatively small thicknesses and angles (a few up to ~ 50 µm, wedge angles ~10^{-5} rad, beam incident angles of few to tens angular degrees). Thus, using simplified approach we present below some computing treatment (Figure 5a and Figure 5b) and corresponding comparisons and discussions with the experimental results (Figure 5c). The curves with solid line in (a) and (b) give the transmission of the IWS as function of length along the x-axis. The dropped lines in the figures represent the reflection of the IWS. The parameters of the wedges and illumination are given on the pictures. The cases with negligible losses in IWs are considered. The typically observed in the experiments sequences of transmission resonances – solid lines and of reflection, correlate well with the calculated. Only the maximal transmission (and reflection) is lower than 100 %, (down to 83 %) due to the quality of IW fabrication as it was discussed already. As can be seen from the graphs, the IWS represents resonance structure that acts with described already properties, for which the simplified approach for treatment of IWS can be applied.

3.2. IWS operation at combining fiber illumination and a lens

As a next point we have studied the action an IWS with fiber output focused by lens on the IWS's front surface. In most of our experimental investigation were using 65 µm fibers at λ = 0.6328 µm (He-Ne laser, ~ 1 mW) and with near Gaussian distribution of the input and output beams as it is shown in Figure 6(c). The divergence of the beam from the fiber output was $\approx 12^{\circ}$.

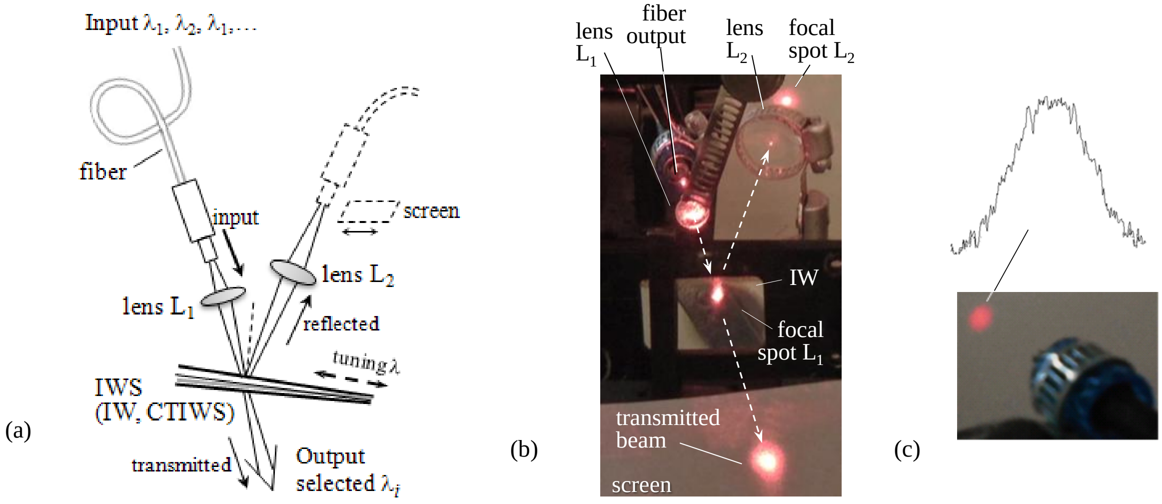


Figure 6. (a) and (b) are present the schematic of experimental and working laboratory arrangements in our investigations. The IWS used is the simplest variant of IW.

In Figure 6 (a) and (b) are presented the schematic of experimental and working laboratory arrangements. The IWS is in simplest variant of IW. The study concerns the realization and investigation of arrangement when the output beam from the used fiber is focalized on the IW. The IW was with optical thickness 5 µm, reflectivity of the coatings $R_1=R_2=0.8$ and apex angle $\alpha=1.2\times10^{-5}$ rad. The composing elements are noted in Figure 6(a) and Figure 6(b). In Figure 6(c) is given also the output of the fiber. The light from the fiber output - at λ=0.6328 µm, 1 mW with near Gaussian distribution (Gaussian diameter of 1.5 mm), is focused on the IW surface by the conveniently placed lens L_1 (5 cm focal length). By sliding of the IW it was found the resonance location, where the beam passes with maximal power (measured maximal transmission ~70 %). Note that the transmitted power can be varied by sliding of the IW around the resonance maximum and thus select the needed transmitted power. The non-transmitted power of the beam is reflected back by IW and is further focused by the conveniently disposed second lens L_2 (7 cm focal length) and thus directed as input beam into the second fiber, treating for second port with other convenient IW.

In the picture is shown the spot of focusing of the reflected beam (near Gaussian distribution with diameter of ~ 0.2 mm in the focalizing spot). The sliding of the IW does not change the direction of propagation for the formed beams. The selectivity strongly depends on the properties and quality of the used IWS. It can be very high when thick IW with high mirrors reflectivity (90%) is used. It can reach parts of nm and less in range of ~ 10 nm. The transmissivity is of order of 10 %. Appling our proposed CTIWS, we reach the same and better selectivity, combined with a few times higher spectral range.

3.3. Shematic of long distance working WDM system

Starting from the experimental results and the discussions above we describe here the proposal with experimenal realizaton-test of multi-ports, each with indipendent selected wavelength and power, WDM composition with possibiliy for long distance between the ports (meters, handred meters and more). The action of the WDM system can be easily understood following the presented already investigations. The system (Figure 7) is composed by suitable combination of IWS elements, optical fibers and lenses. It is based on the discussed in details optical properties of IWS. The multi-wavelengts (multi-communication channels at λ_1, λ_2, λ_3 …) light propagates in fiber which output is focused by short-focal lens L_{11} to the surface of the first IWS_1 component. By sliding IWS_1 is tuned to select the desired wavelength (λs') from the wavelengths in the fiber light and with needed power, thus forning Output 1 and the first port (port 1) of the WDM. The non-used light is reflected and focused by lense L_{12} in the input of the second optical fiber that is connected with second structure IWS_2 by lense L_{21}. The selection by simple sliding of the sheet-like IWS_1 in its plane does not disturb the direction of light propagation . The second fiber transmitts the reflected light to the second combination of lenes and structure (L_{21}. L_{22}, IWS_2) and the action is the same as in the first port –formation of second output (second port) with selection of needed wavelength (cahnnel) with needed power. In such way can be formed system with many ports with desired indipendent wavelengths and output powers. The ports are connected by the optical fibers with different desired lengths – tens meters, handred meters, etc.

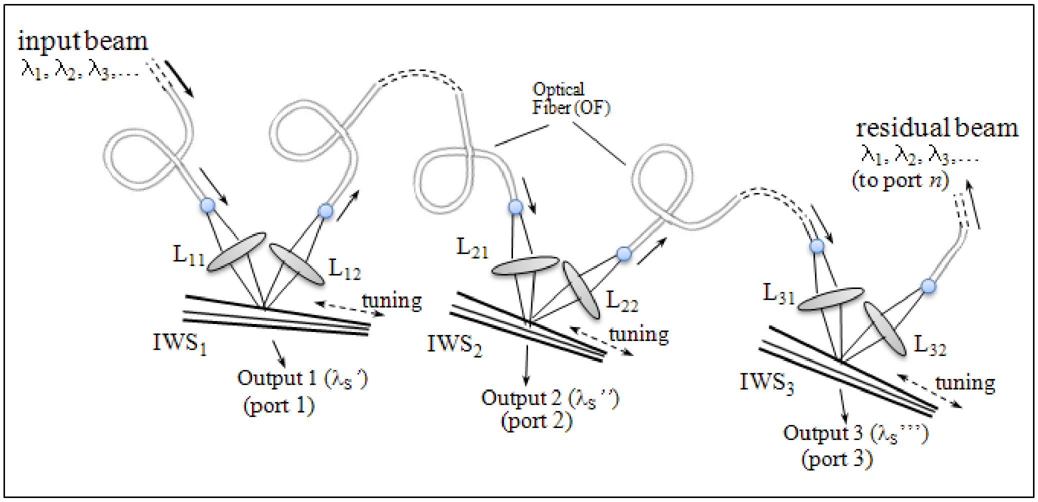


Figure 7.The composed WDM multi-ports system using suitable combination of IWS elements ,optical fibers and lenses. It is based on the optical properties of IWS. In the system $IWS_{1,2,3}$ are coveneient IWSs; $L_{11,12,}$ $L_{21,}$ $L_{22,....}$ are the corresponding convrninient short-focal lenses. The wavelength and power selection for each port are chosen by simple sliding of the corresopnding sheet-like IWS in its plane that does not disturb the direction of light propagation in the system and selection in other ports. The system can consist of many ports at large distance from each other.

3.4. Laboratory realised experiemnal-test model

The experimental WDM system can be understood on the base of schematic, presented and discussed in Subsection 3.3 (Figure 7) and the photographs in Figure 8, with the given notations. For demonstration, we have chosen the variant with IWSs as IW with relatively low selectivity (~ 0.1-0.2 nm) with mirror reflectivity of 80%, optical wedge thicknesses of 3 μm and wedge angle 1.2×10^{-5} rad. The incidence angle was ~7^o. The system contains two ports, which demonstrate its action. Each port is composed by corresponding IW and two short-focal lenses (L_{11} and L_{12}; L_{21} and L_{22}) placed suitably as it was described in Subsections 3.2 and 3.3. As fiber here, we have employed 3 m long thick fiber ~ 1 mm.The input laser beam is closely coinciden beam at two diferent wavelengths (colors). The emission is combined from two He-Ne lasers – red, at 0.6328 μm and yeloow, at 0.5941 μm, with powers each of few mW. All elements are noted in bottom photograph in Figure 8. The IWs are fixed on translating tables that ensure their smoothly sliding. In the top photograph is given the case when for the port 1 the IW_1 selects the red line as Output 1. In the second port, IW_2 is also tuned to selecte red line. As the nex step, by sliding the IW_1, in the port 1 is selected the yellow line. In port 2 remains the selection of red line. Of interest are the bottom photographs, which illustrate the controled variation of the transmitted power (example for port 1) with small sliding of the IW_1 arrownd the maximum of the selected resonance. The small change of the position of the incident beam with respect to the resonance maximum, changes the transmited power as it can be seen fron the figure and text therein. This can be used as additional advantage to control the transmitted power in the selected line.

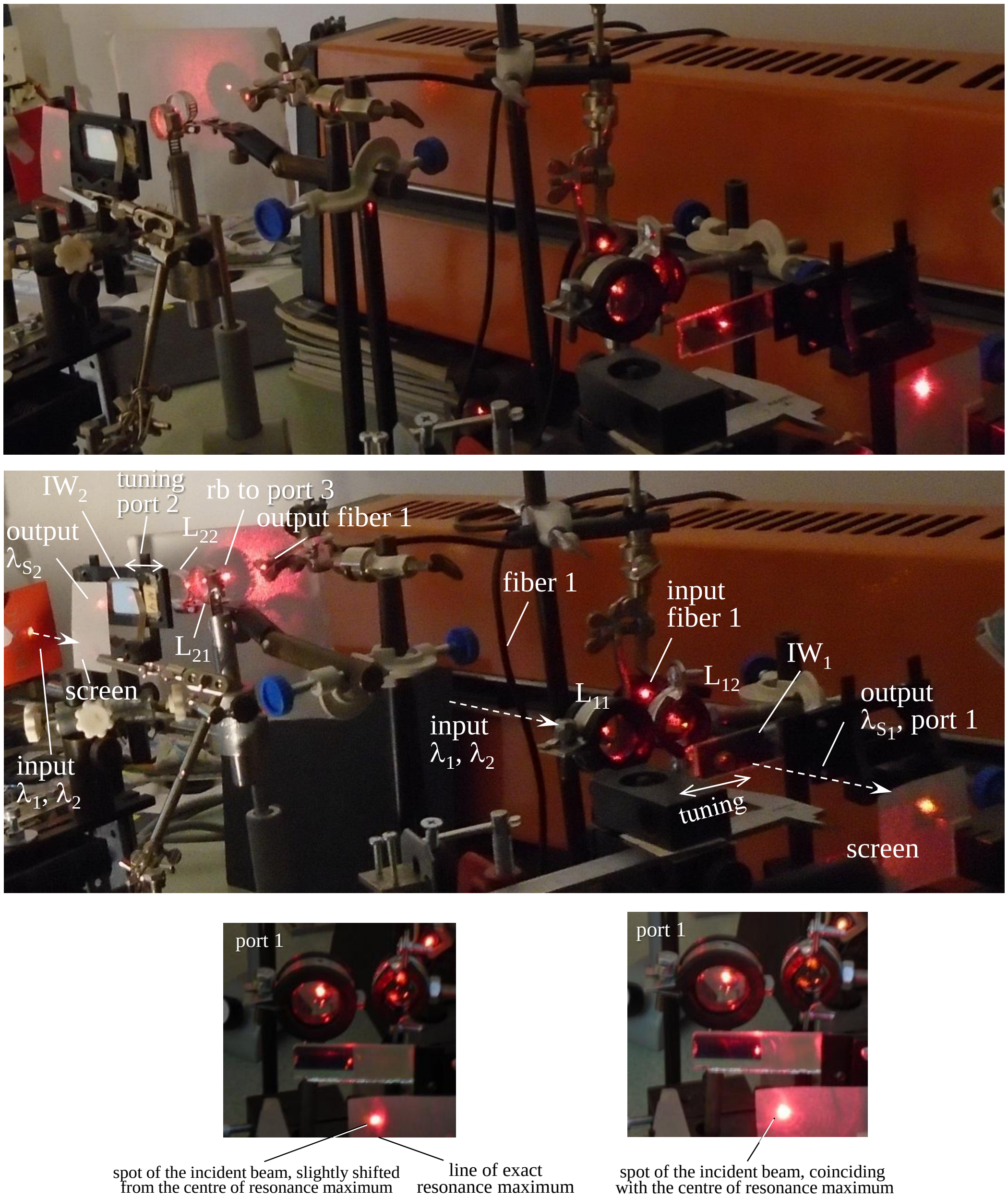


Figure 8. Top and middle - photographs of the laboratory working WDM system based on IWS incorporated in optical fiber setup with focalization of the light beam. The system, realized in practice, is the schematic in Figure 7. For the demonstration of the system action two ports are realized (with IW_1 and IW_2). The composing elements are noted in the middle photograph. The incident beam is composed of coinciding beams from two He-Ne lasers –red, at 0.6328 μm and yellow, at 0.5942 μm. The independent tunable selection is demonstrated for port 1 - in the top figure is selected the red line, in the middle - the yellow line. For the port 2 remains for both cases the red line. Bottom photographs - the controled output power for port 1 with small sliding of the IW_1 arrownd the maximum location of the selected red resonance.

CONCLUSION

In the work we report a new development of our proposed compact WDM element, based on the use of Interference Wedged Structures. The development includes incorporation of such solution of WDM in optical fiber system and work with focused incident beam. In the work we have presented, studied, analysed, discussed and shown that the Interference Wedged Structure can work usefuly with focused incident beams, especialy being output from optical fiber. The objective of such research is enabling creation of multi-port WDM structures for optical fiber communications with long distance between the ports at keeping all advantageous features of the IWS-based WDM elements. We have extended and shown also with experimental test the realistic possibility for creation of such advantageous system. The new WDM system with focalased incident beam employs a specific useful properties of Interference Wedged Structures and conserves and enlarge this advantages. The system operates as a multi-ports with precisely controllable wavelength selection (resolution better than part of nm) within the range of more than 10 nm, with controlled continuously variable transmission from 1-3 to 70 %. The non-transmitted power with the residual non-selected and completely reflected light is directed to the next output - port (loss of the system can be ~ 5% and less). The WDM-structure works at completely independent spectral selection of each port (output/input) without any influence between the tuning of the others.

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