# Interference Wedged Structure for Remote and Purely Optical Intensity Control of a Powerful Laser Beam with a Low-Intensity Light

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*Abstract* – **We develop our proposed devices, compact instruments for controlling powerful light by light, based on Interference Wedged Structures (IWS) that allow tuning for desired wavelength. The device (acting as optical transistor) exploits that the IWS's (CIWS's) gap with saturable absorber can be additionally illuminated by control light beam directly from the top open side of the IWS. The device can be used in scientific apparatus for laser pulse formation and in optical communication systems operating in high electromagnetic noise.**

*Keywords* – **purely optical control of light with light.**

## I. Introduction

Based on our many years of experience in the development and application of interference wedge structures (IWS) and lasers [1-3], and especially the new attractive type, composite interference wedge structures (CIWS), as a suitable combination of IWS [3-5], here we propose and develop optical elements with wavelength tuning capabilities using pure optical light control. The proposed devices also employ the principle of additional, controlled, bleaching of the saturable absorber ($Cr^{4+}$:YAG) appropriately used in optical devices [6,7]. The working device has some similarity to the electronic transistor, i.e., we call it an "optical transistor" (OT). Its physical basis lies in the fact that we apply the ability to control the transmission of IWS (and CIWS) in a highly sensitive and easily realizable purely optical way using a second low-power external light. This light directly illuminates, without loss, the saturating absorber in the CIWS gap. Such an "optical transistor" and the applied systems composed of it can have useful applications in purely optical systems in scientific work, for light pulse formation, and in optical communications, especially when operating under conditions of high external electromagnetic noise. OT based on IWS and CIWS can operate in a controlled manner and be tuned at different wavelengths.

### A. *The principle of the device based on IWS and CIWS for light control by light and working at different wavelengths*

Fig. 1 shows drawings that present the principle of operation of IWS and CIWS type interferometric devices. IWS and CIWS [4,5] are presented schematically with parameter notation, and the approach to their practical implementation is also shown. IWS are two reflective surfaces with a small angle between them ~ 10-5 rad, separated by a transparent gap (air, glass, liquid, plastic). A CIWS is a superposition - a combination of a series of superimposed IWS - mirrors, transparent gaps with appropriate angles and thicknesses, with appropriate superimposition on each other. When the light beam illuminates the IWS or CIWS, each of the light beams, due to the multiple reflections from the mirrors, forms a series of interfering light waves which, by interference with each other, form the transmitted light field as a transmitted light beam.

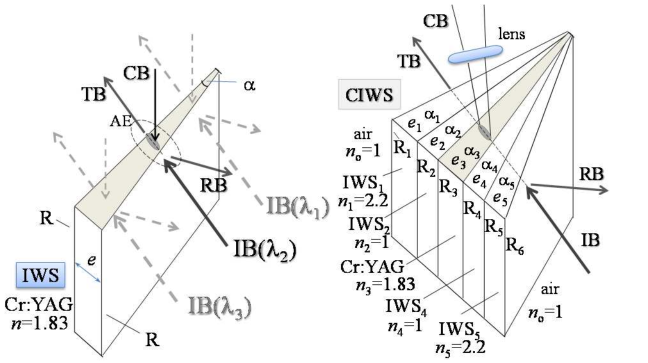


Fig. 1. Schematic of IWS structures with one gap (left) and CIWS with multiple gaps (right). The spaces and substances used in the gaps are also given by their refractive index: the examples are for glass with $n$ = 2.2, $Cr^{4+}$:YAG (noted as Cr:YAG) with $n$=1.83 and air ($n_i$=1); R and $R_i$ ($i$=1,2,...,5) denote wall side mirror with its reflectivity for the corresponding side wall and, in the case of pure glass, is given by the Fresnel formulas of the refractive indices of the two sections separated by the wall; $\alpha_i$ and $e_i$ for the composite IWS are the apex angle and initial thickness, respectively. IB, RB, and TB denote the incident, reflected, and transmitted beams, CB indicates the controlled beam, and AE is the effective area around the surface illuminated by CB.

It is well known from the general theory of the single gap IWS - i.e. Interference Wedge (IW) [8] that when the IW is illuminated by a parallel monochromatic beam of large spatial size (especially a laser beam) of wavelength $\lambda_i$, the transmitted light forms along the wedged arm a series of transmitted parallel linear places - the so-called Fizeau lines (FL). The locations of these resonant lines, the transmission areas, given by their lines of maximum transmission, are equidistant $x = (\lambda_i /2n)$ . tanα and of thickness given by the

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relation $k \cdot (\lambda_i/2) = e_i \cdot n \cdot \cos\theta$, where $k$ =1,2,3... is an integer and θ is the incident angle for the laser beam IB with respect to IWS front mirror (wall), $R_i$ is the reflectivity of the $i$-marked wall-mirror and $n$ is the refractive index. The transmission width of these linear locations strongly depends on the reflectivity of the side mirrors, the wedge angle and the light losses in the gap (i.e. its transmissivity T). As we showed in [3], CIWS allows to select a single, very narrow spectrum (part of nm) line tuned in a large spectral range of hundreds nm. CIWS also allows, for suitable parameters, obtaining around its FLs high (~50mm) and linear transmission variation (from ~100% to ~10%) by simply sliding a sheet like CIWS in its plane. The direction of propagation of the incident, transmitted and reflected beam is retained. The actual implementation and operation of a single IWS and a composite CIWS of two and three IWSs are shown in Fig. 1, where the incident, transmitted and reflected beams are also given. As shown in the figure, the IWS can be realized as a solid material, a transparent wedged gap with multi-dielectric mirrors on both sides (the schematic on the right). A CIWS can be composed of superimposed IWSs similar in construction, but as we have shown recently, it can be realized using high refractive index pure glass, which provides some significant advantages.

*B. The analysis and modeling approach*

The analysis models a saturable absorber introduced into the gap, which can be rapidly bleached and returned to its initial state. As such a saturable absorber, we have taken the $Cr^{4+}$:YAG crystal with a literature reported ~4 ns relaxation time [6,7] and shown a variability of initial and final absorption to obtain transmission from 0.4 to 0.85 [6,7] for a wavelength of 1064 nm (Nd:YAG laser source). Transmissivity is a function of the intensity of the illuminating light. In the modelling, two variants were investigated, presented schematically in Fig. 1, where the corresponding notations are also given. The first is an IWS with the parameters given in Fig. 1, and uses sides with a dielectric mirror R of 95% to 85% (study for several reflections around this one). The second object of study is our proposed pure glass CIWS of few constituent IWS, one or two of them, is made entirely of $Cr^{4+}$:YAG crystal with the mentioned characteristics The other composing structures are as follows: the first one is of pure glass with Fresnel reflection walls defined by the difference in refractive indices of the structure on both sides of the wall (e.g. $n$=2.2 and $n$=1, etc.) as it is given in Fig.1. Similarly for the other structures of CIWS noted in Fig.1, the reflectivity of the wall is determined by the Fresnel reflectivity of the corresponding combination of refractive indices on both sides of the wall under consideration (the Fresnel reflectivity $R_i = (n_i - n_{i-1})^2 \times (n_i + n_{i-1})^{-2}$ for each wall is noted and calculated as described for the first wall). Thus, the proposed CIWS is pure glass and is formed in the described manner with the defined wall reflections. Between $IWS_1$, $IWS_2$ and $IWS_4$, $IWS_5$, is placed the operating $IWS_3$ (with walls with corresponding Fresnel reflections). This $IWS_3$ is formed from a properly prepared $Cr^{4+}$:YAG crystal. Such a formation has significant advantages to avoid the use of problematic mirrors with multi-dielectric coatings, operation at very high operating power densities (as with pure glass) and easy maintenance. As we discuss below, we also investigated a CIWS composed of 7 IWSs with two gap elements realized by a $Cr^{4+}$:YAG crystal.

*C. Analytical description and computer simulation.*

We will briefly present the approaches used for analytical consideration - mathematical treatment and computer adaptation for CIWS structures, following our paper [1]. The general description of the transmission and reflection of IWS and CIWS is based on the interference of the formed multi-beam funnel of rays. Hereafter, we present the principle of both, as well as details of the second one related to its computational adaptation and use. Analytical and computational calculations for IWS are possible based on our developed and published precision approach [1].

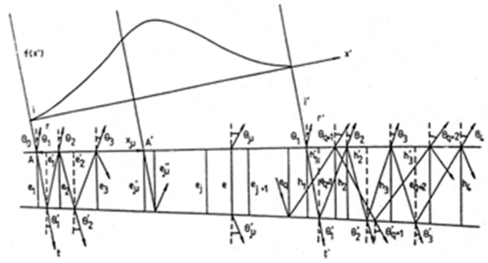

Fig.2. General approach for mathematical treatment of the IWS.

This approach [1] is related to the analytical consideration of the beam paths in the structure taking into account the complexity of the optical paths and summation accordingly. The accumulated difference in optical paths is determined for each interfering beam at a given point on the wedge surface and the distribution of the transmitted and reflected intensities $I_{T,R}(x,\lambda)$ is calculated taking into account the phase differences of the complex amplitudes of the multiple reflected beams, respectively for a given wavelength, where $x$ is the coordinate on the surface (Fig.2). The analysis gives for the transmitted intensity:

$$I_T(x,z,\lambda) = \alpha^2 T^2 (S_1^2 + S_2^2) \quad (1)$$

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

where $\Omega_p$ and $\varepsilon_p$ are functions of x, z, $x_0$, $z_0$, the wavelength λ, incident angle θ, and apex angle α.

We also developed a second model to mathematically describe the action of the IWS based on a reasonable approximation of the IWS as a sequence of Fabry Perot interferometers (FPI) with linearly increased thickness along the wedged arms (noted as the engineering model or FPI approach) [3]. For the typical case of the IWS parameters especially used in the present consideration (α ~ 0.1-5 mrad, ~$0^0$-$15^0$), both models give well acceptable results. This FPI approach yields final formulas that are well adaptable to a computer computation. Fig.3 gives an example for the calculation of the important case of line shapes - reflection R and transmission T. The comparison between the two approaches shows very close results.

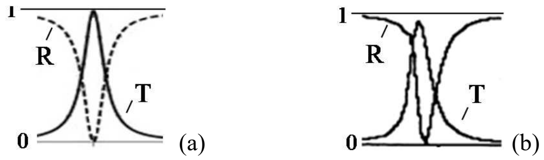


Fig. 3. The computed transmission T and reflection R around the IWS spatial resonance according to the approximate theory (a) and the exact theory (b). He-Ne laser beam (λ= 632.8 nm) [1,3].

For Fig. 3, the used parameters for the FPI – approach (a) are: $\theta=5^0$, $\alpha=5\text{x}10^{-5}$ rad, and for the exact theory (b) for IWS $\theta=5^0$, $\alpha=5\text{x}10^{-5}$ rad, respectively.

*D. Engineering (simplified) analysis approach used*

The basic idea of this approach is to view the IW as consisting of a series of FPIs spaced close together along the length (arm) of the IWS. The sequence has a linearly increasing (or decreasing) interferometer thickness following the IWS thickness, and with appropriate parameters that result in matching the selected FLs for all IWSs. Mathematically, the approach combines the FPI transmission expression T [3] with our added expression for the linearly varying thickness of the IWS. For our considerations, for the example with single gap IWS, the reflectivity of the composed mirrors (i.e. walls) are equal $R_i= R_{i-1}=R$. For the CIWS presented in Fig. 1 of each composite $IWS_i$ structure, the sides of the walls have different reflectivities $R_i$ and $R_{i-1}$ due to the different refractive indices of the substance in the gaps of the structure. Thus, according our approach, the computer simulation combines formula (3) for the FPI transmission T with the expressions (4) and (5), the last introduced and modified by us as it is given below:

$$T = \left(T_i T_j T_l\right) \cdot \left[\left(1 - \sqrt{R_i R_j} \cdot T_l\right)^2 + 4 \cdot \sqrt{R_i R_j} \cdot T_l \cdot \sin^2(\delta/2)\right]^{-1} \quad (3)$$

where $$\delta(x) = \frac{2\pi}{\lambda} \cdot 2 \cdot e(x) \cdot n \cdot \cos\theta \quad (4)$$

and $$e(x) = e_0 + x \cdot tg\theta \quad (5)$$

Here $e_0$ is the starting thickness of the structure, $x$ is its distance between the line of starting position of $e$ (i.e. $e_0$) and line of propagation of incident light beam, λ is the wavelength of the incident beam, θ is the angle of incidence of the beam relative to the normal to the CIWS wall (wall 1), $n$ is the refractive index of the corresponding IWS, $R_i$, $R_j$ is the reflectivity of the corresponding walls, $T_i=1-R_i$, $T_j=1- R_j$ . Expression (3) also accounts for losses by the transmission coefficient $T_\ell$ of the absorbing layer (absorption gap) in the structure with the introduced absorber, for the other pure glass structures in CIWS in formula (1), $T_\ell$ is not considered ($T_\ell$ is taken as 1).

A CIWS is analytically considered as a series of IWSs, each of which has its own transmission and reflection characteristics. For optimal transmission, the resonances of the sequential structure are arranged to coincide along the IWS. The incident beam on the CIWS passes sequentially through the first IWS and the passed light enters the next structure and so on in all the structures and forms the transmission beams.

*E. Analysis*

The aim of the investigation is to consider the transmission control given by the transmissivity of the structure T as a function of the intrinsic losses given by the variation of the transmissivity $T_\ell$ of the saturating absorber, which in our consideration will vary between a few % (i.e. ~97%) and 40% - values of practical interest. $T_\ell$ is changed by bleaching the absorber.

The CIWS transmission investigation includes:

- single gap structure
- composite 5-layer and 7-layer CIWS; with single and double gap with $Cr^{4+}$:YAG
- estimation of what percentage of the incident control beam power is on the IWS - substructure with saturable absorber and comparison with the control beam power.

Programming (3) - (5), we can compute for a given $e_0$ the corresponding resonance transmission curve as a function of $e_0$, λ, $k$, θ, α, $n$ and R. For parasitic (uncontrolled) losses less than ~3%, the computational analysis gives results relatively close to the calculations for the ideal lossless cases, and hence such low losses will not be considered.

*F. Transmission dependence T of a single gap IWS with saturating absorber by variable transmission of the gap $T_\ell$*

First, the $T_{IWS_0}$ low intensity incident beam transmittance of the single IWS gap with $Cr^{4+}$:YAG placed in it (i.e., this crystal represents the gap) will be analytically investigated. Schematically, this is shown in Fig. 1 (left). Thus, the study will be for variable $T_\ell$.

The initial parameters used are around those typical for IWS, i.e. for R is 0.9, $e$ = 500 μm, $\alpha= 0.5\text{x}10^{-5}$ rad. As can be seen from the literature [6,7], a laser light density of ~25 J/cm$^2$ can bleach the $Cr^{4+}$:YAG crystal from 99% to 60% at the wavelength λ = 1064 nm considered here. Thus, for the crystal that fills the gap of our CIWS structure and is illuminated by the controlling beam surface, is typically 4 mm wide and 3-5 mm long, and for ~10 mJ of illumination pulse energy, the density is ~100 J/cm$^2$ , which bleaches the $Cr^{4+}$:YAG absorber well in the controlled beam passing region [5-7]. Note that the illuminating fraction of the controlled beam light that initially passes through the 90% reflective wall-mirror of the CIWS is ~10% of the incident beam density. Since the controlled beam has a power density of ~100 J/cm$^2$, only 10 J/cm$^2$ illuminates the $Cr^{4+}$:YAG crystal, resulting in a low IWS transmittance of ~5%; if the controlled beam with an intensity of ~30 J/cm$^2$ illuminates the working range of the gap (Fig. 1, left) directly, this can ensure that the estimated transmittance reaches ~85%, as shown by the given estimation approach. From the described modelling and calculations, the plots given in Fig.4 of the maximum transmittance of the considered single gap structure are obtained as a function of transmittance for $T_\ell$ ranging between 0.8 and 1 (the first value that can be estimated and that is in the literature [6,7] ).

Importantly, the transmission variation plots have linear regions, especially the IWS mirror reflectivity plot of 50%, but in the low percentage range (99% to 60%) and high value. The other plots, especially the one for the reflectance of the mirrors of 90%, reach a very large range (theoretically from 100% to 10%, but with linearity for two small intervals (from 35% to 87% and from 43% to 100%). Such linear ranges are of significant interest for amplification of an intensity modulated controlled incident beam. Thus for modulation, the lines for R = 0.65 and R = 0.5 between 100% and 80% change of the $Cr^{4+}$:YAG crystal transmittance, which filled the IWS gap, are more acceptable.

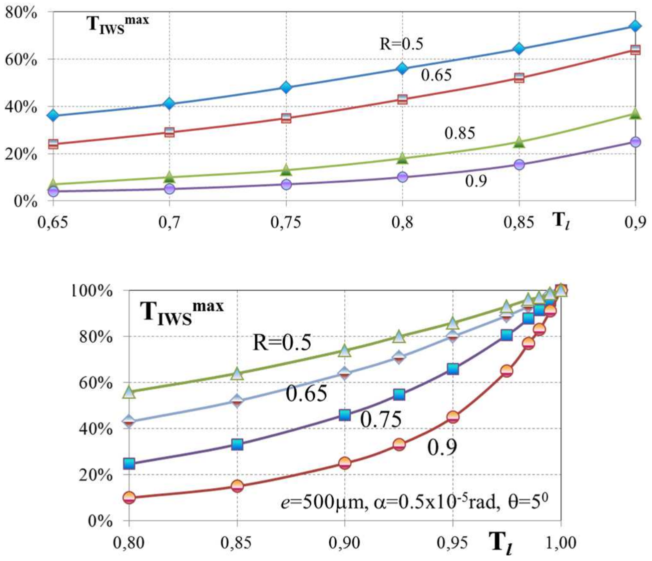


Fig. 4. Computer-calculated transmittance of a single gap IWS (Fig. 1, left) for a change in the transmittance of a gap-filled $Cr^{4+}$:YAG for 4 real values of the reflectance of the composite mirrors and for given IWS parameters. The curves are discussed in the text.

As the next point in the work, we will present the solution for controlled light beam by light based on the application of double substructures of pure IWS glass with 3 and 5 gaps filled by $Cr^{4+}$:YAG crystals as shown in Fig.5. This pure glass structure is similar to the one given and shown in Fig.1 (right) and is composed of 7 gaps as schematically represented in the figure.

This solution is more complicated than the one in Fig. 1, but our study shows that the control efficiency of the passing laser beams is higher than that of the general single gap CIWS with $Cr^{4+}$:YAG. The explanation is related to the fact that these seven IWS, with good synchronization, allow to increase the reflectivity of the composite substructures and the efficiency of the $Cr^{4+}$:YAG action due to the illumination splitting of the longer part of the crystal. It is also important that such a design yields a well-defined linear dependence of transmittance as a function of controlling power, presented by the system transmittance as a function of the overall transparency of the CIWS design.

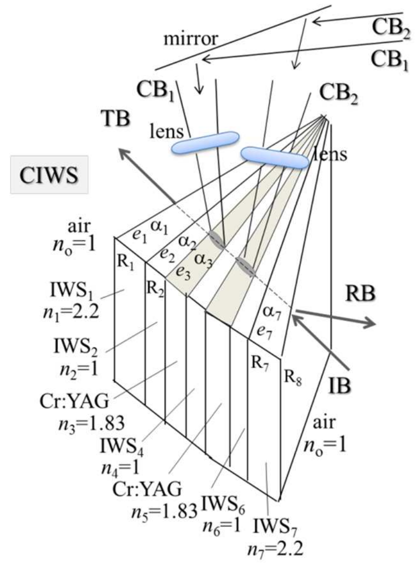


Fig. 5. Schematic of dual $Cr^{4+}$:YAG gaps CIWS. The notations are the same as in Fig. 1. The controlling light beam is split to illuminate the two crystal substructures. The operating wavelength is 1064 nm (Nd:YAG laser beam).

The plot in Fig. 6 presents a typical case of the considered dependence with a well evident linearity of the dependence of the power of the transmitted beam on the total transmission $T_{CIWS}$ of the design, varied by illumination with a controlled beam. Wavelength tuning is performed by sliding the structure.

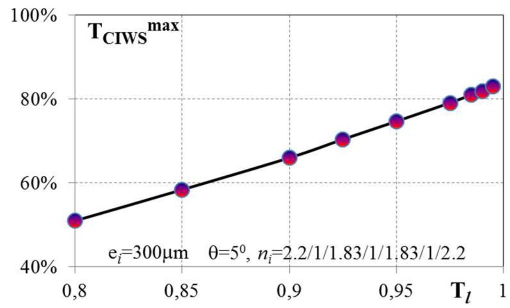


Fig. 6. Typical CIWS transmission dependence case plot with well-defined linearity of the transmission change $T_{CIWS}$ under controlled beam illumination of the $Cr^{4+}$:YAG substructure. The CIWS parameters are given in the graph.

## II. Conclusion

In this work, we present an optical instrumentation solution - spectrally tunable, based on Interference Wedged Structures (IWS) - single IWS and composite IWS (CIWS) for light-by-light control. In the analytical analysis, we demonstrated their capability to linearly control the intensity of the laser beam passed through the structures with an efficient linear control of its power. The devices may find attractive applications in optical devices, in rectangular pulse formation as shown in our previous works [e.g. 5], and in optical communication systems, especially for operation in high electromagnetic noise.

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