Journal of Physics and Technology, Volume 3 (2019) Issue 1, pp. 8-13 *ISSN 2535-0536*

Optimization of Fizeau Wedge Controllable Transmission

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Abstract. The paper presents analysis of the response in transmission for Fizeau interferential wedge in order to use this optical element as a beam splitter with a controllable ratio between the transmitted and the incident power. The wedge is formed by two highly reflecting flat surfaces inclined at a small angle. The power control is achieved by translation of the wedge along its surface. By using an angular spectrum approach for finding the distribution of the transmitted intensity, we have shown that reflectivity of the coatings and the wedge apex angle affect strongly the value of the displacement required for achieving a given change in the transmitted power. The experiments confirm the theoretical predictions.

Keywords: Interferometers, Fizeau wedge, beam splitter.

1. INTRODUCTION

Fizeau or interferential wedge (IW) consists of two reflecting flat surfaces at a small angle between them (Born and Wolf, 1999). This optical element finds applications in laser technology (Deneva et al, 2007), spectral analysis (Kajava et al, 1993; Demtroeder, 2008) and optical metrology (Belmonte et al, 2006; Kumar et al, 2009). The wedge apex angle, reflectivity of the surface coatings and refractive index of the gap form a unique fringe pattern in reflection and transmission under illumination by spatially and temporarily coherent light (Nenchev et al, 2018). The linearly varying thickness along the IW leads to variation of the interference conditions of the partial waves propagating within the wedge and to a change in its transmission. At a given wavelength, transmission reaches maximum at a certain position of a narrow beam impact area on the IW surface. Variation of the transmitted power with the displacement to the left or to the right from the resonant position can be used for control of this power. In other words, the wedge may act as a controllable beam splitter as we have recently proposed in (Deneva et al, 2018). The aim of the present study is to analyze the IW response in transmission as a function of the parameters affecting this response and to choose optimal values of these parameters for achieving effective beam splitting. The task is solved by using the angular spectrum approach for modelling the IW transmission. Some experimental data are also provided.

2. THEORETICAL BASIS

A conventional IW consists of two reflecting surfaces inclined at a small angle, α, which is of the order of tens of micro-radians. The reflectivity of the coatings, R, is usually higher than 50 %, and this leads to multiple beams interference. The gap size between the reflecting surfaces or the wedge thickness, e, is increasing linearly normally to the IW's ridge. For a light beam falling normally to the ridge, the IW's analysis becomes a one-dimensional task. It has been solved by Brossel (Born and Wolf, 1999) for plane wave illumination at wavelength, λ. In this case, the IW forms a sequence of identical transmission peaks known as Fizeau lines in the observation plane behind the wedge. The spatial separation between the peaks is given by $\Delta X = 0{,}5\alpha / \lambda$ for an air-gap IW. The separation is the same along the IW's surface, but one observes different behavior of a thin and a thick wedge in the spectral domain. The thin wedges transmit in a wide spectral interval at a large free spectral range. The thick wedges show spectrally narrow transmission at a small spectral distance between resonances. In other words, the spectral resolution increases with the wedge thickness while the free spectral range decreases.

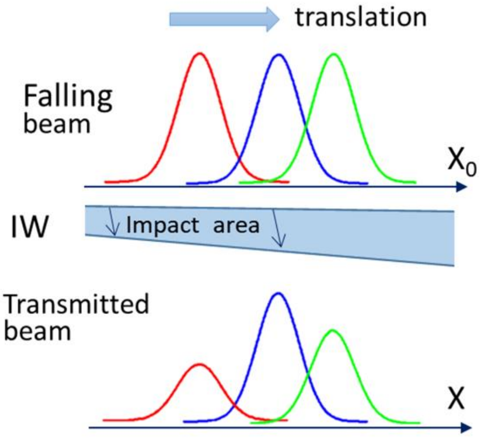

Fig. 1 Schematic representation of the change in the transmitted intensity profile at displacement of the beam impact area from the resonant position. The transmission profiles correspond to Gaussian beam illumination.

For a spatially narrow beam, e. g. a laser beam, the wedge transmission depends on the wedge apex angle, the wedge thickness, reflectivity of the coatings and the refraction index of the gap. Transmission depends also on the spatial width of the beam and the wavelength. The IW splits the falling beam into a reflected beam and a transmitted beam at a negligible energy loss. The transmitted power reaches maximum at a certain resonant wavelength. The maximum power at this wavelength is obtained for a certain resonant thickness. At translation of the IW to the left or to the right from the resonant position, the transmitted power decreases. This is explained in Fig. 1, which depicts the change in the profile of the transmitted beam when the impact area of a Gaussian beam moves along the IW's surface.

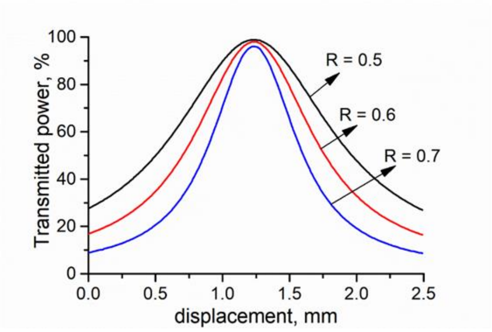

Fig. 2 Normalized transmitted power as a function of the displacement of the beam impact area for an air-gap IW with thickness 50 μm and an apex angle 50 μrad at different reflectivity of the coatings, *R*. The IW is illuminated with a Gaussian beam with $2\omega_0 = 200$ μm. The angle of incidence is 2 degrees, and $\lambda = 632.8$ nm.

The calculations in the paper are made for a Gaussian beam with intensity distribution, $I(x) = \exp\left[-(3 - x/\omega_0)^2\right]$. The beam falls quasi-normally. At a small incidence angle, the resonant transmitted power approaches the incident beam power. The calculation starts at $x_0 = 0$ and covers the beam impact area on the IW surface. We accept that this area is equal to $6\omega_0$ for a Gaussian beam. The transmitted intensity, $I_T(x,d)$ is calculated for a certain IW's displacement, d, from some initial position which can be arbitrarily chosen. The fringe pattern $I_T(x,d)$ in the observation plane is found by the angular spectrum approach developed in (Stoykova et al, 2010). According to this approach, the complex amplitude in the falling beam is represented as expansion of plane waves propagating in different directions in accordance with the angular spectrum of the complex amplitude of the falling beam. The coefficients of the expansion are also determined from the angular spectrum. At the complex amplitude level, the IW's response to the Gaussian beam is found by summation of the responses to the participating plane waves. The IW response to a single plane wave is given by Brossel's formula (Born and Wolf, 1999). The dependence of the normalized transmitted power on the displacement, d, is found from:

$$\rho(d)=\frac{\int_{-\infty}^{\infty} I_T(x,d)\,dx}{\int_{-\infty}^{\infty} I_T(x)\,dx} \qquad (1)$$

As it can be seen in Fig. 2, which gives $\rho(d)$ at different reflectivity of the coatings for a 50 μm air-gap IW with an apex angle 50 μrad, the transmitted power variation is described by a symmetrical curve. This curve has sections of practically linear power change thus providing a possibility for a linear control of the transmitted power by translation of the wedge with respect to the falling beam.

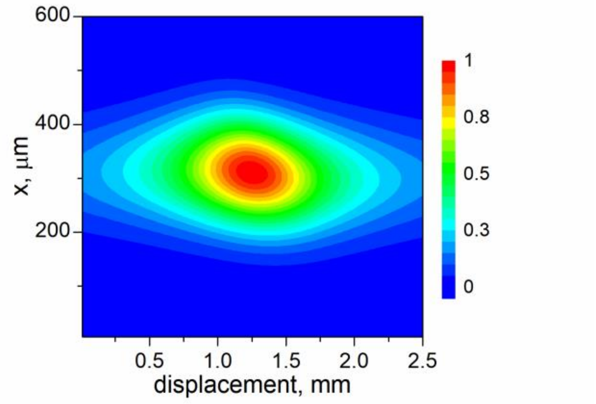

Fig. 3 Transmitted intensity distribution as a function of the displacement of the beam impact area for an air-gap IW with thickness 50 μm and apex angle 50 μrad. The IW is illuminated with a Gaussian beam with $2\omega_0 = 200$ μm. The angle of incidence is 2 degrees, $\lambda = 632.8$ nm and $R = 0.6$.

The transmitted intensity profiles formed by a thin IW are symmetrical with respect to the axis of the falling beam. For thicker wedges, this is valid for the resonant profile whereas the profiles formed by shifting the IW from the resonant position have maxima located to the left and to the right of the falling beam axis. This is seen in Fig. 3 which presents the transmitted intensity profiles behind the wedge as a function of the displacement, d. The wavelength is 632.8 nm, and we consider the case of $\omega_0 = 100$ μm. The falling beam axis corresponds to $x = 3\omega_0 = 300$ μm.

3. IW RESPONSE OPTIMIZATION

To use the IW as a beam splitter with a controllable power ratio, one should analyze how the different parameters affect the curve $\rho(d)$. The most important issue is to find such a combination of the parameters that provides a rather slow increase of the transmitted power with the displacement of the wedge. This makes possible easy and accurate control of the power ratio.

As a first parameter, we studied the influence of the wedge thickness, e. We calculated one of the slopes of the curve $\rho(d)$ for the air-gap IW with a thickness 5, 50 and 100 μm and an apex angle of 50 μrad. The plots obtained for the thickness 5 and 100 μm are shown in Fig. 4. Comparing Fig. 4 with Fig. 2, we may conclude that, at a fixed apex angle and a small angle of incidence, the thickness influence on the wedge response is practically missing. As it should be expected, the slope of the curve $\rho(d)$ is strongly affected by the reflectivity, R, of the coatings. The most interesting section of this curve is the section of almost linear variation of the transmitted power. This section corresponds to different intervals of displacement variation. Thus, at $R = 0.5$, the linear section is observed for displacements d going up to 0.6 mm while at $R = 0.8$ the displacement varies within the interval of 0.25 mm. Therefore, implementation of the IW based beam splitter should be done with lower reflectivity coatings $(R \le 0.6)$. The other advantage of using lower reflectivity is achieving more symmetric intensity distributions in the transmitted beam. This is crucial in view of the requirement of no change of the spatial profile of the transmitted beam for effective beam splitting.

The other studied parameter was the apex angle. The results of computation for an air-gap IW with a 50 μm thickness are shown in Fig. 5 for reflectivity of the coatings equal to 0.6. The curves show that the same variation of intensity is achieved at different displacements. The smaller the apex angle, the larger is the required displacement.

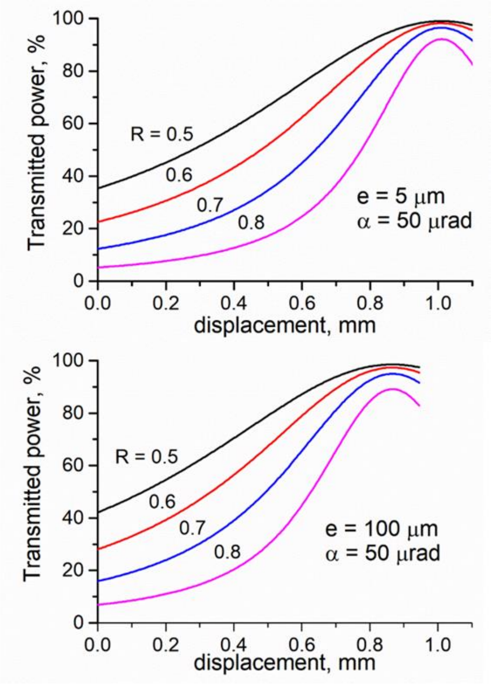

Fig. 4 Normalized transmitted power as a function of the displacement of the beam impact area for an air-gap IW with thickness 5 μm (top) and 100 μm (bottom) at apex angle 50 μrad and different reflectivity of the coatings. The IW is illuminated with a Gaussian beam with $2\omega_0 = 200$ μm. The angle of incidence is 2 degrees, and $\lambda = 632.8$ nm.

To characterize more effectively the influence of reflectivity and the apex angle, we plot in Fig. 6 and Fig. 7 the value of the displacement that must be applied to increase the normalized transmitted power from 50 % to 60 % as a function of the reflectivity and the apex angle respectively. The results are practically the same for all studied wedge thicknesses. Obviously, reflectivity less or equal to 0.6 and apex angles up to 50 μrad should be used.

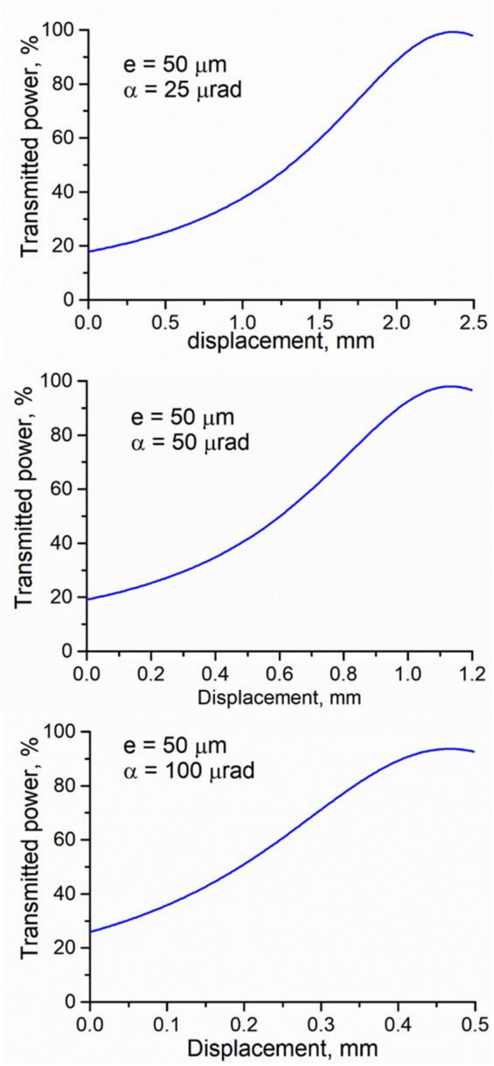

Fig. 5 Normalized transmitted power as a function of the displacement of the beam impact area for an air-gap IW with thickness 50 μm at an apex angle 25 μrad (top), 50 μrad (middle) and 100 μrad (bottom) at reflectivity of the coatings equal to 0.6. The IW is illuminated with a Gaussian beam with $2\omega_0 = 200$ μm. The angle of incidence is 2 degrees, and $\lambda = 632.8$ nm.

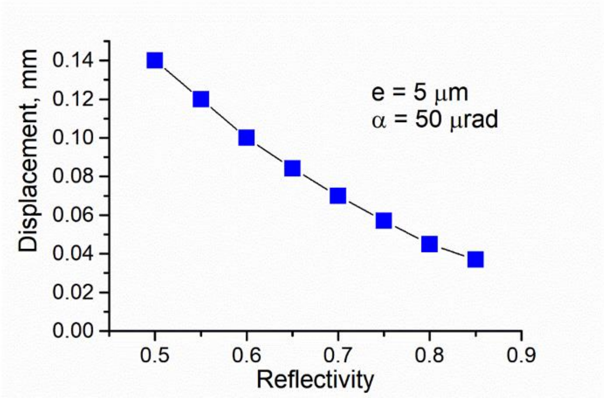

Fig. 6 Displacement of the beam impact area for changing the normalized transmitted power from 50% to 60% as a function of reflectivity. Calculation is made for an air-gap IW with thickness 50 μm at an apex angle 50 μrad under Gaussian beam illumination with $2\omega_0 = 200$ μm. The angle of incidence is 2 degrees, and $\lambda = 632.8$ nm.

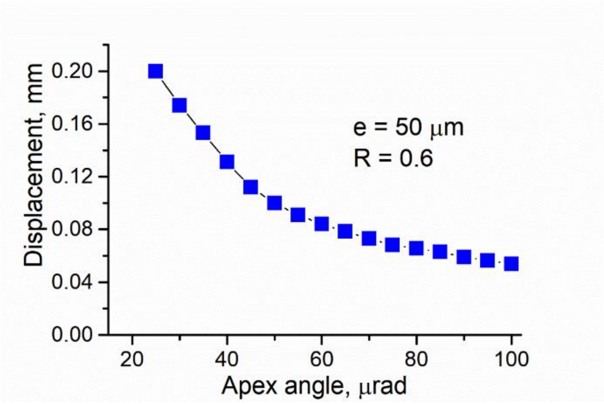

Fig. 7 Displacement of the beam impact area for changing the normalized transmitted power from 50 % to 60 % as a function of the apex angle. Calculation is made for an air-gap IW with thickness 50 μm at an apex angle 50 μrad under Gaussian beam illumination with $2\omega_0 = 200$ μm. The angle of incidence is 2 degrees, and $\lambda = 632.8$ nm.

For experimental study we used an air-gap IW with thickness $e = 5$ μm, $\alpha = 12$ μrad, gap refraction index $n = 1.5$, reflectivity of the mirrors equal to 0.65 and a He-Ne laser emitting at wavelength $\lambda = 632.8$ nm. The angle of incidence was 5°. The incident power was 15.6 mW. The transmitted power at the resonance was 8.9 mW or ≈ 57 % of the incident power. The reflected power was 5.4 mW or about 35 % from the incident power. The measured values indicate that there is about 8 % loss related to the absorption in the layers of the mirrors. We measured the transmitted power as a function of the IW's displacement with respect to the falling beam. The results are shown in Table 1 which presents the normalized transmitted power as a function of the displacement from the resonant position. The power was measured for equal displacements to the left and to the right from the resonant position.

TABLE 1 Normalized transmitted power in percents as a function of the displacement, d, in mm from the resonant position

$d = 0$	1	2	3	4
to the left from the resonance				
75	45	22	17	10
to the right from the resonance				
75	49	22	17	9

4. CONCLUSIONS

In summary, we have studied the response in transmission of Fizeau interferential wedge in order to use this optical element for controlling the ratio between the transmitted and the incident power in the case of illumination with a spatially narrow beam. The power control is achieved by translation of the wedge in the plane of its front surface. This changes the resonant conditions and provides controllable power variation. We calculated the curve giving the transmitted power as a function of the displacement from the resonance for a wedge thickness in the range of 5 – 100 μm, a wedge apex angle from 25 to 100 micro-radians and reflectivity of the coatings from 0.5 to 0.8. Transmission was calculated for a Gaussian beam illumination using an angular spectrum approach. We obtained that the apex angle and reflectivity had a strong influence on the width of the power-versus-displacement curve. The influence of the thickness was negligible. We found that reflectivity should be no greater than 0.6 and that an apex angle smaller than 50 micro-radians provided slow enough increase of the power at the wedge translation for accurate power adjustment. The power-versus-displacement curve has sections of almost linear power variation with the displacement. However, linearity of this variation is not an obligatory requirement to perform controllable beam splitting because one can calibrate the wedge beforehand.

ACKNOWLEDGEMENTS

This work was supported by Bulgarian Science Fund, project DN-17/7 "Elements and devices in optics and quantum electronics on the base of wedged interferential structures for laser technology, optoelectronics, optical communications, metrology and spectrum analysis." Equipment of INFRAMAT (Research Infrastructure from National roadmap of Bulgaria), supported by Contract D01-155/28.08.2018 with Bulgarian Ministry of Education and Science is used in the present investigations.

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