Design and fabrication of multilayer dichroic beam splitter

Vemuri SRS Praveen Kumar[1, 2], Parinam Sunita[1,2], Mukesh Kumar[1], Neelam Kumari[1,2], Vinod Karar[1], Amit L Sharma[1, 2]*

[1]CSIR-Central Scientific Instruments Organisation, Sector 30C, Chandigarh, 160030, India
[2]Academy of Scientific & Innovative Research (AcSIR), Sector 30C, Chandigarh, 160030, India

*Corresponding author: Tel: (+91) 9417850180; E-mail: amitsharma_csio@yahoo.co.in

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Abstract

Beam splitters are primarily used for applications like avionic displays, optical storage, fluorescence applications, optical interferometry, semiconductor instrumentation where some of the information needs to be reflected as well as transmitted. They operate on the principle of light being reflected and transmitted by various interfaces where it is split by percentage of overall intensity or wavelength. In this study, design and fabrication of a dichroic optical beam splitter for filtering of red and green light from a white light source has been presented. Here, a symmetric dielectric multilayer stack with 15 alternating layers of alumina and silica are deposited on BK-7 glass using e-beam evaporation technique. High and low refractive indices of 1.63 and 1.46 respectively are used with quarter-wave optical thicknesses of layers. The beam splitter is designed for 45˚ angle of incidence using Filmstar^{TM} design software. Transmission spectrum obtained from UV-Vis-NIR double beam spectrophotometer shows reflectance of ~54% at 660 nm (red wavelength region) and transmittance of ~88% at 550 nm (green wavelength region). The coated sample is further subjected to adhesion and hardness test according to MIL standard and no peel off or scratch is observed indicating excellent durability of the coating. The modelled and measured results closely agree with one another over visible spectral regions. Copyright © 2017 VBRI Press.

Keywords: Thin films, optical coatings, beam splitters, optical properties.

Introduction

Multilayer dichroic beam splitters (splits the incoming light into number of spectrally distinct output beams) are a kind of polarization separators that are based on optical interference principle. These filters play an important role in sensitive research experiments such as optical interferometry, holography, phase conjugation, optical image processing, aviation industry, optical storage, laser based measurements, etc. [**1-7**, **17**] where proper splitting of beams is needed. To achieve it, a proper design of beam splitter is important. Several studies are reported on different kinds of beam splitters and their applications in various fields. In optics, three types of beam splitters are considered i.e. free space, holographic, and wave guide [**3**]. This paper is concerned with 'free space beam splitter' which operates on the principle that when a certain intensity of light is incident on one surface, a part of light is reflected and remaining part of light is transmitted through various interfaces which is shown in **Fig. 1**. Thin film beam splitters usually come in two main configurations, plate and cube beam splitters [**1**, **2**, **4**, **5**]. In Plate type beam splitters, multi layers are deposited on the plane substrate while in the cube form, layers are deposited on the hypotenuse of two prisms and then prisms are cemented with an optical adhesive (adhesive used is equivalent to the substrate refractive index) to produce a cube.

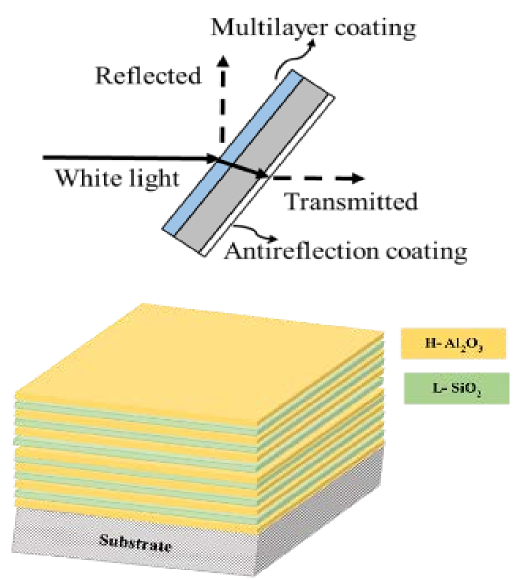

Fig. 1. Schematic showing the transmission and reflection of light through interfaces in dichroic beam splitter.

Beam splitters consist of a thin film coating on two surfaces. The first surface is coated with multilayer dielectric coating with partially reflecting properties in either the visible, the UV or IR spectrum and other surface is coated with antireflection coating optimized for 45 degrees [**8-11**,**18**]. Although the operation of the beam splitter is conceptually simple, its performance characteristics can dramatically affect the accuracy and repeatability of the overall system. In this work, a multilayer stack with 15 alternating layers of alumina and silica are deposited on BK-7 glass using e-beam evaporation technique. High and low refractive indices of 1.63 and 1.46 respectively are used with quarter-wave optical thicknesses of layers. The beam splitter is designed for 45˚ angle of incidence using Filmstar™ design software. These kind of beam splitters are used in complex optical systems for image processing, optical system with laser radiation as well as in radio therapy medical field, avionics display system.

Design concept

The design concept consists of following stages:

(a) Choose a pair of layer materials of high and low refractive indices.

(b) Select the central wavelength and number of layers for the design.

(c) Calculate the quarter wave optical thickness using the formula:
Optical thickness (O.T) = Physical thickness (n) * Refractive index (R.I)

(d) Construct the design equation for the chosen number of layers and optimize it using thin film design program.

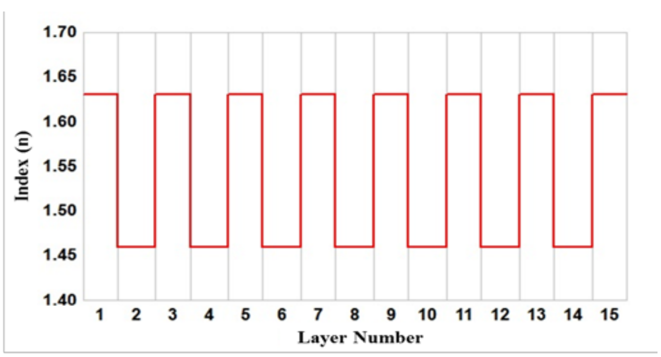

Fig. 2. Quarter wave design of 15 alternating layers of Al_2O_3 and SiO_2.

Design of dichroic beam splitter

This design shows the concept of dichroic beam splitter for achieving 57% reflectance at red wavelength (660 nm) and 90% transmittance at green wavelength (550 nm). The substrate used is BK7 and angle of incidence is 45°.

Step 1: The materials chosen for the design is Al_2O_3 and SiO_2 with indices H=1.63 and L=1.46 respectively.

Step 2: We construct 15-layer quarter wave design with peak wavelength (λ = 660 nm) as shown in **Fig. 2**.

Step 3: Distribution of the layers results in the following stack: Air / (H, L) 7 H/ Sub and effective thickness of the stack is written as: 1/ (0.25H, 0.25L) 7 0.25H/ 1.52.

Step 4: Simulate the above design using the Filmstar™ software and calculate the reflectance and transmittance.

Experimental

Materials and methods of preparation

Alumina and silica multilayer thin films were deposited on BK-7 glass substrates of 70 x 70 mm size. Deposition was performed in high vacuum (2.4 x 10^{-5} mbar) using 99.99 % pure alumina and silica in the form of powder by electron beam evaporation technique. All the alternate layers are deposited with quarter wave thickness for the wavelength 660 nm. Thickness was measured in-situ by Quartz crystal thickness monitor (Intellimetrics IL820).

Electron beam evaporation parameters

Before starting the deposition process, each material was pre-melted for half an hour for achieving proper rate of evaporation during multilayer deposition. During deposition, entire chamber is maintained under reactive oxygenated environment with an oxygen partial pressure of (2 x 10^{-4} mbar). For better uniformity of the films, the substrate holder was rotated with 12~15 rpm throughout the process. Further, the substrate was maintained at a temperature of 250° C during the deposition process to achieve proper adhesion. The schematic of electron beam [**13**] evaporation coating (PLS 570 coating system, Pfeiffer Vacuum) plant is shown in **Fig. 3** and list of deposition parameters maintained during deposition is shown in **Table 1**.

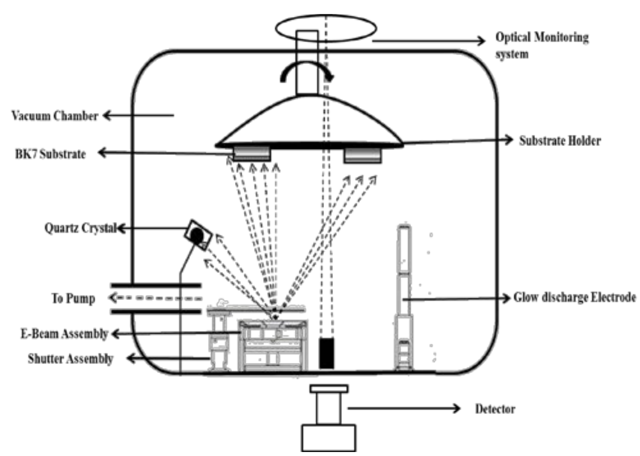

Fig. 3. Schematic of E-beam evaporation plant.

Characterization techniques

The UV-Vis reflectance spectra of the Al_2O_3/SiO_2 multilayer films were collected using a double beam UV-Vis spectrometer (Cary 5000, Agilent). The adhesion of the multilayers were tested using MIL standard cellophane tape. Hardness test was carried out for the films using rubbing pad with ISO standards.

Table 1. Deposition parameters of electron beam evaporation.

S. No.	Deposition Parameters	Corresponding Values	
1	Substrate temperature	250 °C	
2	Initial Base pressure	$2.432x10^{-5}$ mbar	
3	Substrate Used	BK7	
4	Oxygen Gas Pressure	$2x10^{-4}$ mbar	
5	Glow Discharge gas	Argon (Ar)	
6	Density	Aluminum Oxide 4.0 g/cc	Silicon dioxide 2.2g/cc
7	Melting point	2046°C	1710°C
8	Transparency range	0.19 - 7 µm	0.2 – 9 µm

Further to test the sample, an experiment (**Fig. 4(a)**) was performed where a white light source was incident at 45° on the coated side of the beam splitter in a dark room, it was observed that the reflected light was red color and transmitted light was green color as expected (**Fig. 4(b)**).

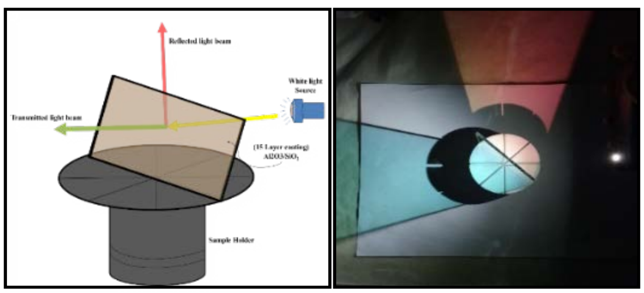

Fig. 4. (a) A schematic of Beam Splitter (b) An experimental setup used for testing of Beam Splitter.

Results and discussion

Optical investigation

Fig. 5 illustrates the modelled and measured reflectance spectra of dichroic beam splitter with 15 number of layers. The optical performance of the dichroic beam splitter is obtained by alternate layer deposition of alumina and silica using e-beam evaporation technique. Reflectance spectra is obtained using UV-Vis-NIR double beam spectrophotometer (range 400-800 nm) which is the most commonly used technique for spectral analysis of thin films. It is observed that reflectance peak decreased by 3% in the measured spectra as compared to the theoretical spectra. However, there is no change in full width half maximum (FWHM) of modelled and measured spectra. Due to the time lag in achieving the required rate of evaporation for a particular material (after shutter opens), there was a variation in the deposition rate during the coating process. The decrease in amplitude and minor deviation of the measured spectra from the modelled one can be due to the variation in the optical and physical properties (n and k, density) of the deposited material as compared to the n and k values assumed for the design [**14-16**].

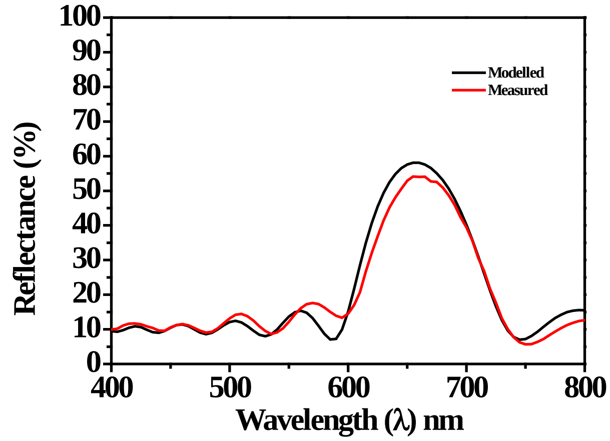

Fig. 5. Reflectance Vs wavelength spectra of Dichroic beam splitter.

Film quality test

To test the durability of the coating, the coated samples were subjected to MIL standard adhesion (no. MIL-F-48616) and hardness tests.

Adhesion test

For adhesion test [**12**], ½” wide cellophane tape conforming to type I of L-T-90 (MIL-C-48497A) was applied on the surface of the film and was then removed suddenly with a jerk at an angle normal to the surface. The quality of the coated film was assessed by examining the coated surface for any peel-off or deformity of the film. The coated sample passed the test as no such peel-off was observed.

Fig. 6. Film quality test for dichroic beam splitter.

Hardness test

The coated sample was further subjected to a moderate abrasion using hardness tester [12] as per MIL standard no. MIL- C-675. The rubbing eraser conforming to MIL standard MIL–E-12397 was rubbed across the sample from one point to another over the same path for 30 strokes. The abrasion tester was held approximately normal to the surface under test during the rubbing operation and a force of 2.5 pounds was applied as shown in **Fig. 6**. It was observed that there was not any visible scratch on the sample surface.

Conclusion

The dichroic optical beam splitter is designed and fabricated for reflecting and transmitting light in red and green wavelength respectively. The Measured and modelled Reflectance spectra shows ~3% decrement in peak amplitude and with no variation in FWHM. The fabricated beam splitter can be used in the application of radio therapy in medical field, display devices in avionics. Quality of the coated film was tested by subjecting it to MIL standard adhesion and hardness test and no peel off or scratch was observed indicating excellent durability of the coating.

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Author’s contributions

Conceived the plan: VSRSPK, VK, ALS; Performed the experiments: VSRSPK, MK; Data analysis: NK, PS; Wrote the paper: VSRSPK, PS, ALS. Authors have no competing financial interests.

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