Full length article

Metal–dielectric broad-angle non-polarizing beam splitters with ultrathin copper layer

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ABSTRACT

A novel metal–dielectric three-layer cube broad-angle non-polarizing beam splitter (nPBS) with an ultra-thin copper layer was designed, prepared and characterized. Our nPBS structure (270 nm thick) is optimized around the wavelength of 1064 nm (reflectance in between 25 and 35% and transmittance in between 55 and 65% for the incidence angle range of 35–55°). For comparison, a 24-layer design for 45° incidence angle solution (6193 nm thick) using dielectric–dielectric nPBS was shown. For manufacturing point of view, reducing the layer number in the coating let eliminate undesirable mistakes during preparation of every layer thickness and decrease the time of whole structure fabrication. During or after multilayer deposition it is necessary to minimize the possibility of metal oxidation by choosing material with low affinity to oxygen. Additionally, it is important to reduce the product price by avoiding more expensive metals like gold and silver. Our nPBS structure was prepared in a single process by using of magnetron sputtering. The measured transmittance and reflectance values are in agreement with the design and the target values. Every single layer thickness error analysis was done.

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1. Introduction

Non-polarizing beam splitters (nPBS) are widely used in optical system. Their aim is to divide incident light into transmitted and reflected beams in a certain ratio. Conventionally nPBS are usually operate at oblique angles of incidence. At oblique angles of incidence (for example, inside the glass cube) s- and p-polarized light tends to be different. In this case, a big challenge of a high interest is to obtain the same transmittance and reflectance for both s- and p-polarized light. Furthermore, the nPBS should have a reasonable angular field for alignment.

Several designs of nPBS were previously suggested in literature. They could be done from all–dielectric multilayer coating [1–6]. In this case, multilayer coatings consist of low and high refractive index layers such as metal oxides or metal fluorides. The many layer coating construction is complex and difficult in manufacturing. Additionally, optical properties of every single layer may be additionally influenced by the preparation conditions [7]. Moreover, a very big thickness of coating may give a shift of the incident beam. The thinnest nPBS design wins, as it was at "Optical Interference Coatings Design Contest 2007: triple bandpass filter and non-polarizing beam splitter" [8].

Recently, it was suggested using of grating for the nPBS structures [9,10]. Nevertheless, it is difficult to fabricate this kind of optical components due to large thickness of the grating groove. Moreover, preparation of such structures could not be done in a single process.

Other possibility to reduce number of nPBS layers is using of metal layer instead of dielectric layer. Ultra-thin metal layer has a smaller depolarizing effect than dielectric. Previously, it was reported about use of Ge [11], Al [12], Ag [13,14] and Au [15] layers for nPBS. To the best of our knowledge, up to now [16], no effort has been made to prepare beam splitter using copper layer.

During multilayer preparation the growth of ultra-thin metal layer could be affected by a higher affinity to oxygen left in residual atmosphere in the deposition chamber or introducing during reactive deposition of oxide layer. Additionally, it is necessary to minimize the possibility of metal oxidation after the deposition in order to prevent changes in coating optical properties. In all these cases metal should have low affinity to oxygen. The standard enthalpy of oxides formation for Al, Ge, Cu, Ag and Au are −1675.7 kJ/mol (Al_2O_3) [17], −580.0 kJ/mol (GeO_2) [17], −157.3 kJ/mol (CuO) [17], −31 kJ/mol (Ag_2O) [17] and −3.4 kJ/mol (Au_2O_3) [18], respectively. For optical coatings it is necessary to compare optical properties. For Al, Ag, Au, Cu and Ge extinction coefficients (refractive index) at the wavelength of 1064 nm are 9.25 (1.03) [19], 7.77 (0.09) [19], 7.44 (0.13) [19], 7.24 (0.12) [19]

and 0.36 (4.72) [20], respectively. Among mentioned elements, Al and Ge have much higher enthalpy of oxides formation and Al has the highest extinction coefficient. Au, Ag and Cu seem to be the most promising candidates. Finally, if compare the price of nPBS device manufacturing it will be much cheaper to use copper than gold or silver.

For fabrication, as a dielectric material, niobium oxide was selected. Niobium oxide films possess unique physical and chemical properties, such as high refractive index, excellent chemical stability and laser irradiation resistance, as well as low optical absorption in the visible and near infrared light spectrum [21–23]. This results in their wide implementation in optical interference filters, beam splitters, high-reflectivity and anti-reflective coatings, as well as other functional coatings applications.

For modelling, as a low refractive index material, silicon oxide was used. Silicon oxide is a common low refractive index material for multilayer coatings (see e.g. Refs. [1,22,24,25]).

In this work, we designed, prepared and characterized a new cube broad-angle nPBS device that is based on the metal–dielectric three-layer structure, where as metal suggested to use copper. The nPBS structure is optimized around the wavelength of 1064 nm (reflectance 25–35% and transmittance in between 55 and 65% for the incidence angle range of 35–55°). All the nPBS multilayer structure was made by magnetron sputtering in a single process. Optical properties and surface roughness were investigated.

2. Experimental details

The niobium oxide and copper layers were deposited using an unbalanced magnetron source (Torus™ sputter gun) with a planar niobium (99.95% purity) and copper (99.95% purity) targets in a Kurt J. Lesker sputtering system (PVD225). The system was initially pumped down to a base pressure below 3×10^{-7} Torr.

The magnetron was driven by a pulsed DC power supply (Advanced Energy Pinnacle Plus). In this work, the repetition frequency was 100 kHz, the duty cycle was 80% and the fixed power was 600 W and 500 W for copper and niobium, respectively.

All process gases used for deposition were >99.999% pure. The Ar flow rate was 20 sccm and the pumping speed was adjusted to attain the argon pressure at the same value of 2.2 mTorr. The settings of the Ar flow rate and the pumping speed were not changed during the processes. Prior every deposition, the target was pre-sputtered for 5 min in Ar to remove any surface oxides. The detailed description of reactive magnetron sputtering and characterization of niobium oxide layers is given in previous work [21]. Recently, a novel method for monitoring the conditions of continuous copper layer formation was suggested by us [26]. In present work, layer thickness was controlled by quartz crystal and broadband monitoring system. These monitoring strategies are well known [27], widely applied for optical coating manufacture and their simultaneous use gives reliable control of deposition process.

Cube nPBS consists of a pair of right angle prisms cemented together. It has anti-reflective (AR) coatings on external surfaces and a non-polarizing beam splitting coating applied to the hypotenuse of one of the two prism (Fig. 1). The beam splitting coating was deposited onto rotating (20 rpm) hypotenuse of polished fused silica (FS) right prisms (size 25.4 mm) and double-sided polished FS substrate (25.4 mm diameter, 1 mm thickness). Square sides of prisms were covered with the AR coating (Table 1). The AR coating was made to minimize losses and reduces ghost reflections (mentioned, for example, in Ref. [28]).

The coatings target specification for cube broad-angle nPBS is given in Table 1. Working laser wavelength of 1064 nm is widely used. One of examples using beam splitter for the wavelength 1064 is give in Ref. [29].
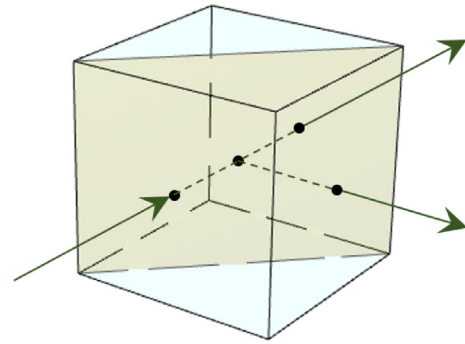

Fig. 1. Schematic illustration of cube non-polarizing beam splitter. It consists of a pair of right angle prisms cemented together. The metal-dielectric beam splitting coating is applied to the hypotenuse of one of the two prisms.

Table 1
Coatings target specification for the preparation of cube broad-angle non-polarizing beam splitter. The values of transmittance, T, reflectance, R, and angle of incidence, AOI, for anti-reflective, AR, and non-polarizing beam splitter, nPBS, coatings at the wavelength of 1064 nm are given.

Coating	Single surface transmittance	Single surface reflectance	Polarization
AR	T > 99.5% @1064 nm	R < 0.3% @1064 nm	Unpolarized
nPBS	55% < T @1064 nm AOI 35–55° < 65%	25% < R @1064 nm AOI 35–55° < 35%	s and p

Surface topography was measured using a Dimension Edge atomic force microscope, AFM, (Bruker) in tapping mode, over a 10 μm × 10 μm scan area. The AFM probe was an Al and diamond-like carbon (DLC) coated Si probe of <15 nm tip radius.

The film optical constants (refractive index, n, and extinction coefficient, k) of every layer were determined from transmittance and reflectance spectra, using the software "OptiChar" from Opti-Layer Ltd [30]. This software incorporates the following models for n (λ) and k (λ) determination: $n(\lambda) = n + \frac{A}{\lambda^2} + \frac{B}{\lambda^4}$; $k(\lambda) = B_0 \exp\left(\frac{-B_1}{\lambda} - \frac{-B_2}{\lambda}\right)$; transmittance-reflectance spectra are fitted by adjusting the A, B coefficients and physical thickness of the film until the discrepancy between theoretical transmission and the measured spectrum were minimized. For single layer characterization, transmittance, T, and reflectance, R, spectra were measured with the angle of incidence, AOI, (in reflection) 8° in the 300 < λ < 1400 nm wavelength range using a Photon RT (Essent Optics) spectrophotometer. For nPBS coating characterization, T and R spectra were measured for s- and p-polarized light for the incidence angle range of 35–55°.

Multilayer coating structures for nPBS were designed with the software "OptiLayer" from OptiLayer Ltd [30].

3. Results and discussion

3.1. Non-polarazing beam splitter design

In this part, we introduced the solution for the target (Table 1) and compared results for dielectric-dielectric and metal-dielectric materials combinations. The three materials we used in design were silicon oxide, copper and niobium oxide (Table 2). The silicon oxide and niobium oxide extinction is negligible in comparison with the copper film. The optical constants of layer materials depend on the process and parameters used for the deposition. Before multilayer coating modelling, niobium oxide and copper films were deposited by magnetron sputtering on FS substrates and characterized.