Surface & Coatings Technology 241 (2014) 54–58

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Laser-based assessment of optical interference filters with sharp spectral edges and high optical density ☆

Mark Ziter, Gary Carver, Sarah Locknar *, Tim Upton, Bob Johnson

Omega Optical, 21 Omega Dr, Brattleboro, VT 05301, United States

ARTICLE INFO

Available online 5 October 2013

Keywords:
Interference filters
High optical density
Laser testing
Rocking curve

ABSTRACT

Interference filters have improved over the years. Sharp spectral edges (>1 db/nm) reach high optical density (OD > 8) in a few nm. In-situ optical monitoring to within 0.1% error enables these levels of performance. Due to limitations related to f-number and resolution bandwidth, post-deposition testing in typical spectrophotometers cannot reveal the quality of today's filters. Laser based measurements at selected wavelengths prove that blocking above OD8 to OD9 is manufacturable with high yield. This paper compares modeled spectra and laser based measurements.

1. Introduction

The advances in thin-film design software and automated, computer-driven deposition systems have made it possible to create the most demanding optical filters. It is not unusual for filters with cut-on and cut-off edges to exceed 2 OD/nm in steepness. The cut-on (50% transmission) to OD 6 transition can occur within as few as 60 cm^{-1}. [1] These types of filters are commonly used in laser applications where the signal of interest is very close in wavelength to the laser line, such as Raman spectroscopy. Another application is the very narrow atomic line filter (such as the H-alpha) used in astronomy.

The OD (or blocking) of a filter depends heavily upon the application. Of course, the OD required for a particular application is a function of the intensity (J/s) of the light one is trying to block (interfering signal) and the integration time of the detection system. For a wavelength of 488 nm, in a system with a μJ/s interfering signal and an integrated detection time of 0.1 s, an OD of 11 gets the interfering signal down to about 2 photons. In contrast, when a much shorter integration time is used (on the order of 100 ns), an OD of 5 is sufficient to reach the same level. Other factors should also be considered by the customer, including the wavelength range of the required blocking, peak blocking versus average blocking over that range and price.

Design of these types of filters presents a challenge as the manufacturer has to balance several factors, the first of which is a trade-off between a very steep edge and ripple in the passband. For a dielectric stack of a given number of layers, reducing ripple at the transmission peak causes a decrease in the edge steepness. This tradeoff can be countered by increasing the total number of layers, but then other factors such as the length of the deposition and stress in the films become more important. Film stress (especially in thick > 10 μm stacks) can be large enough to warp the substrate [2,3], while exceedingly long deposition times reduce manufacturability and increase cost.

Once a design is developed and deposited on a substrate, the manufacturer is faced with the limitations of the test equipment at hand. Most thin-film companies are equipped with scanning spectrometers which employ a grating or prism and slits. While convenient, the nature of these scanners introduces a wavelength broadening of the measurement equal to the spectral bandwidth of the instrument. The use of a broadband source will always lead to a distribution of wavelengths coming through the slit. This will manifest itself as a decrease in measured edge steepness as the transmission of the very steep edge filter under test is convolved with the spectral bandwidth of the spectrometer (Fig. 1). The typical strategy is to reduce the slit size, but this reduces the incident light intensity, which in turn limits the OD that can practically be measured.

To further complicate the measurement in a standard scanning spectrometer, many sample chambers contain a convergent beam geometry that produces a number of angles of incidence (AOI) with the sample [8]. Most thin-film optical filters are designed to work at a single AOI. The peak transmission wavelength of a bandpass filter designed to work at normal incidence will be shifted to lower wavelengths at other AOIs (Fig. 1). The band shape may also be distorted at other angles because of polarization effects. The spectral AOI-dependence in the sample chamber is difficult to model because the AOI range in the horizontal and vertical directions is often different in the sample chamber. One strategy has been to aperture down the beam in the sample chamber to reduce the number of AOIs hitting the sample. This again reduces the incident light intensity, thus reducing the

☆ This manuscript is based on work presented at the Society of Vacuum Coaters 56th Annual Technical Conference in Providence, Rhode Island, April 20-25, 2013.

* Corresponding author. Tel.: +1 802 251 7371.
E-mail addresses: mziter@omegafilters.com (M. Ziter), gcarver@omegafilters.com (G. Carver), slocknar@omegafilters.com (S. Locknar), tupton@omegafilters.com (T. Upton), rjohnson@omegafilters.com (B. Johnson).

0257-8972/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.surfcoat.2013.09.054

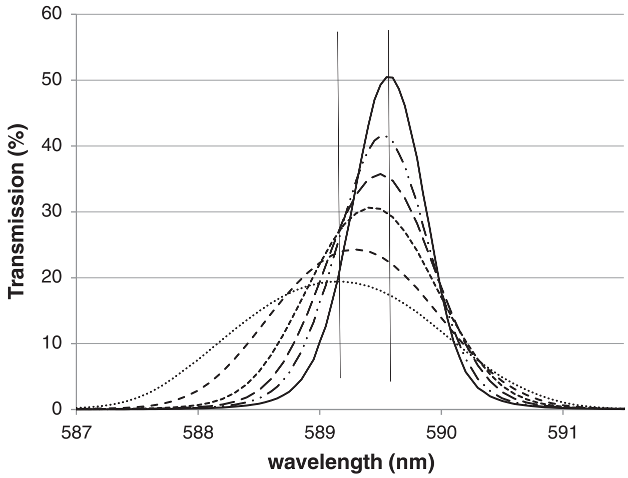

Fig. 1. Measurements of thin-film optical filters are influenced by the spectrometer settings. A bandpass filter measured at 6 spectral bandwidths ranging from 0.1 to 2 nm. Broadening is caused by the increase in spectral bandwidth while the center wavelength shift (vertical lines) is due to an increase in the AOI distribution when the larger slit is used.

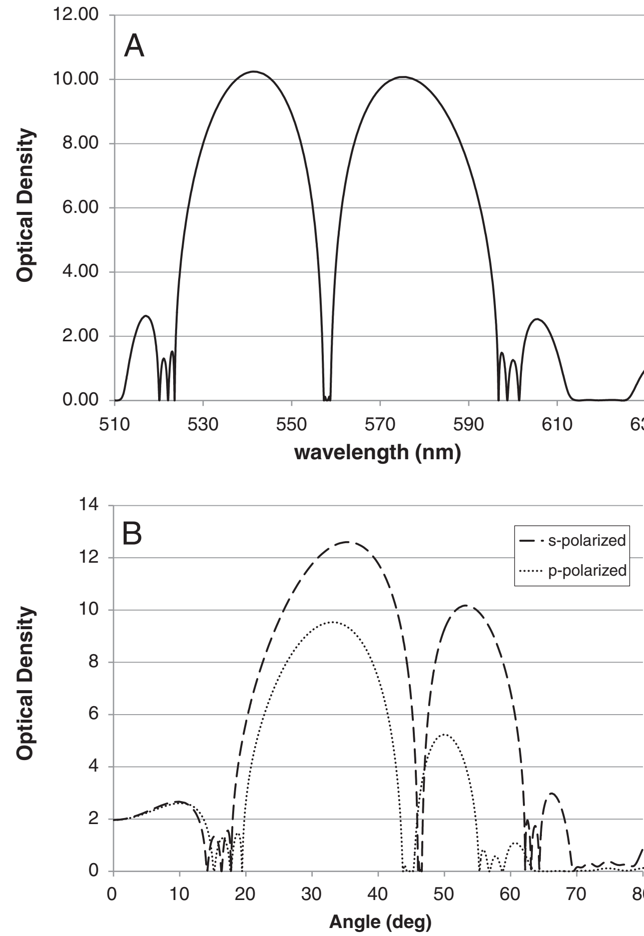

Fig. 2. A Fabry–Perot design of 54 layers showing (A) the expected spectral response at normal AOI and (B) the expected AOI response at 514.5 nm. Note that there is a difference in the response of the two polarization states.

measurable OD. At very low light levels, one also approaches the detector's noise floor. This is the main reason most spectrometers will not read above about 6 OD.

In theory, one should be able to deconvolve the measured spectrum using the instrument response function (a function that includes both the spectral dispersion and angular dispersions described above) to give a "true" spectral response of the filter. However, in order to do the deconvolution accurately, one has to measure the instrument response function directly. This is extremely difficult and adds noise to the measurement which complicates the deconvolution process.

While the AOI-dependence of a filter is a nuisance in a spectrometer, it can be used to explicitly measure spectral edges with a laser. [4] By rotating a filter in the laser beam, the transition edges can be "rocked" into transmission or reflection as illustrated in Fig. 2. Edges always shift to the blue at larger AOI. This can be exploited to measure filters in the entire visible wavelength range using a small number of discrete laser wavelengths. If the edge is above the laser wavelength and within about 50 nm, the filter can be rotated until the light passes through (or gets blocked) by the impinging light (Fig. 2). This method utilizes a fixed, linear polarization and a single wavelength. Contamination by other states of polarization causes an increase in the background signal and limits the measurable range. A properly polarized laser allows for measurements up to 9 OD where the detector reaches the noise floor.

In this paper, we detail a method that combines a number of spectral scans, angle rocking curves and thin-film modeling to predict the response of the deposited film to very high ODs- beyond the measuring capabilities of most optical systems.

2. Materials and methods

A 54-layer Fabry–Perot design was deposited onto a glass plate using thermal vacuum evaporation. The system was detuned so that the spectral response across the plate was not uniform.

For the tunable-laser measurements, we used an Agilent tunable external cavity laser (model 81640A) fiber-coupled to an OFR free-space bench and an Agilent optical power monitoring head (model 81624A). The wavelength was tunable from 1520 to 1630 nm. The linewidth was approximately 0.4 pm and the center wavelength accuracy was 2 pm. The amplified spontaneous emission (ASE) floor is estimated to be 40–55 dB below the peak power. The wavelength tuning and power meter output are controlled by a LabView (National Instruments) program developed in house.

For the laser-rocking curves, we used an s-polarized Spectra-Physics Ar^+ laser line at 514.5 nm. A Newport UE404S rotary stage was used to rotate the sample at 0.5 degree increments. Measurements were made using a Newport power meter (head model 818-SL, meter model 1830-C). The Newport MM3000 controller for the rotary stage and the power meter are controlled by an application consisting of a pair of synchronous co-programs developed in house using National Instruments' Windows/CVI.

3. Theory/modeling

Starting designs were simultaneously reoptimized to match the output of 3 spectrometer scans (at normal and 45 degree AOI over the range of 300–2500 nm with a 2 nm slit and at normal incidence from 500 to 600 nm with 0.5 nm slit) and the tunable laser scan. This large dataset was used because it provides complimentary pieces of information. The spectrometer scans provide a large wavelength range at relatively low resolution, while the tunable laser scan provides a small wavelength range at high resolution. The optimization was performed using the "reverse engineering" mode of the Essential MacLeod software. All 3 parameters (thickness, density and inhomogeneity) were adjusted sequentially until convergence. The fully converged reverse engineered design was then used in a simplex optimization using the rocking curve data, laser scan and the normal AOI spectrometer scan as targets. Spectrometer readings below 0.05% T were set to zero. The rocking curve and laser scan were weighted more heavily because of their higher precision. Data values greater than 6.5 OD were set as a