Demonstration of optical interference filters utilizing tunable refractive index layers

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Abstract: Optical interference filters utilizing tunable refractive index layers are shown to have higher spectral fidelity as compared to conventional filters consisting of non-tunable refractive index layers. To demonstrate this increase in spectral fidelity, we design and compare a variety of optical interference filters employing both tunable and non-tunable refractive index layers. Additionally, a five-layer optical interference filter utilizing tunable refractive index layers is designed and fabricated for use with a Xenon lamp to replicate the Air Mass 0 solar irradiance spectrum and is shown to have excellent spectral fidelity.

OCIS codes: (310.4165) Multilayer design; (310.1620) Interference coatings.

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Optical interference filters have been the subject of extensive research over several decades [1–5]. The ability to control the transmittance and reflectance of light utilizing optical

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interference filters is of interest in many optical applications. One application is to modify the spectral power distribution of an incident light source in order to replicate the Sun's spectrum for use in solar simulators [6]. The key parameters in the design of such optical filters are the refractive index, thickness and absorption coefficient of each layer. Because of the general lack of transparent dielectric materials with desired refractive index values, a great deal of optical filter research has focused on the use of so called Herpin equivalent layers to obtain refractive index values not readily available [7–9]. Here we present optical interference filters with multiple discrete layers, consisting of transparent nanoporous thin films deposited by oblique angle electron-beam deposition. These nanoporous thin films allow for direct control over the refractive index and thickness of each layer in an optical coating. In addition to their ability to be tuned to *any* refractive index, within a broad range of values, it has been shown that such nanoporous films have enabled extremely low refractive index values, close to that of air [10]. Whereas in the past the refractive index has been a material constant, the refractive index now is a freely tailorable parameter thereby widely expanding opportunities in optics and photonics [11]. Here it is demonstrated that these two characteristics, namely a tailorable refractive index and a very large refractive index contrast, are significant advantages in the design and ultimately the performance of optical interference filters. Filters utilizing tailorable refractive index layers are shown to enable a higher correlation to the desired output spectrum with fewer layers and/or less average reflectance than filters utilizing non-tunable refractive index layers.

The spectral transmittance of optical interference filters to modify Xenon-lamp spectra into a planckian black-body spectra at 5780 K were calculated for a variety of layer numbers and allowed maximum average reflectance values. In these calculations, multi-layer optical interference filters utilizing tailored low-refractive index layers with allowed refractive index values between 1.10(n_{low}) – 2.54(n_{high}) are compared to filters utilizing non-tunable refractive index layers of SiO_2 and TiO_2. A Xenon-lamp was chosen as the pre-filtered spectrum across the wavelength range of 400 – 1600 nm. The Xenon-lamp's normal incidence transmitted spectra (after optical filters) were calculated according to the transfer matrix method [12]. Optical filters were designed and optimized using a genetic algorithm [13]. The genetic algorithm is an iterative, computational method that borrows the evolutionary concept from biology, and includes selection, mutation and combination, to 'design' an optimized optical interference structure. This optimization procedure is accomplished by an iterative sequence: First, a large population of optical interference filters, with a fixed number of layers, is randomly generated, with the two free parameters for each layer being refractive index (n_{low} – n_{high}) and thickness (5nm – 500nm). Second, the filter structures are sorted by their "fitness" based upon a figure of merit. Third, a percentage of the worst performing structures is discarded, and replaced by crossover and mutation of a randomly selected pair of the remaining fit structures. This sequence is then repeated until convergence on an optimized structure is achieved. For our design of these filters, the figure of merit was chosen to be the correlation coefficient, r_{xy}.

$$r_{\text{xy}} = \frac{\sum_{i=1}^{N}(x_i - \overline{x})(y_i - \overline{y})}{S_{\text{x}} S_{\text{y}}}. \tag{1}$$

The correlation coefficient is a measure of the similarity between the post filter Xenon-lamp spectra, x_i, and the *desired* spectrum, y_i, i.e. either the theoretical planckian black-body at 5780 K or the Air Mass spectrum 0 (AM0) [14]. In Eq. (1), S is the standard deviation defined as

$$S_{\text{x}} = \frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{x})^2. \tag{2}$$

The summation, Σ, is carried out over the wavelength range of interest. In practice, the figure of merit for the design of a filter may be tailored to a variety of application-specific

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requirements. For these calculations, in addition to the correlation coefficient, an upper limit was placed on the maximum allowable average reflectance for a given optical filter. Filters with maximum average reflectance values higher than this limit were automatically rejected and replaced. Figure 1 (a) – (c) compare filters that utilize tunable refractive index layers to filters utilizing non-tunable refractive index layers.

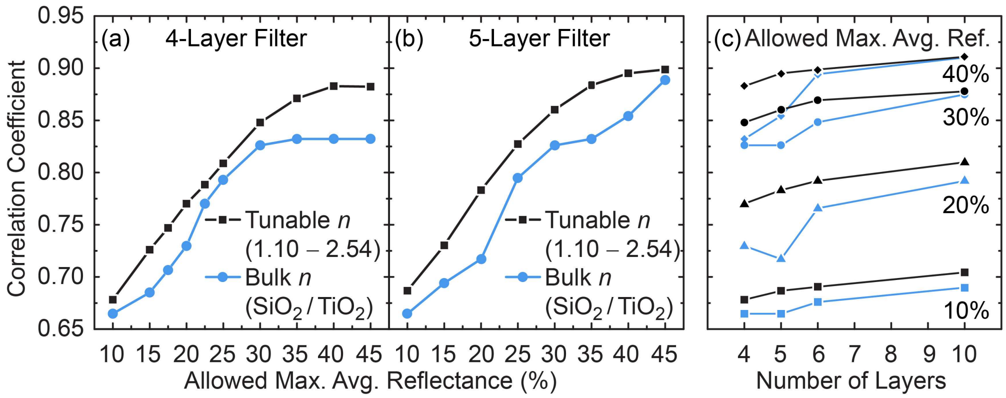

Fig. 1. (a), (b) Correlation coefficient as a function of allowed maximum reflectance for 4- and 5-layer optical interference filters utilizing both tunable and non-tunable refractive index layers. (c) Correlation coefficient as a function of the number of layers for both tunable and non-tunable refractive index layers.

Figure 1(a) and 1(b) show the correlation coefficient of both tunable and non-tunable optical interference filters designed with 4- and 5-layers over a range of allowed maximum average reflectance values. We note that when the maximum allowable reflectance of an optical interference filter is increased, the spectral fidelity also increases. However this effect saturates, whereby further increases in the allowed maximum allowable average reflectance does not translate to increases in the correlation coefficient. It should also be noted that increases in average reflectance come at a cost to the total output power transmitted through a filter. In Fig. 3(c) the correlation coefficient is plotted as a function of the number of layers for 10, 20, 30, and 40% allowed maximum average reflectance for both tunable and non-tunable refractive index layer structures. The figures reveal that the correlation curves of filters utilizing tunable refractive index layers are smooth over all ranges of layer number and allowed maximum reflectance values. Whereas filters designed with non-tunable refractive index layers have distinct dips in their correlation curves. These figures can be explained by two significant advantages in utilizing tunable nanoporous layers for optical interference filters: First, Fresnel's equations suggest that the magnitude of a reflection coefficient, *R*, at an optical interface is maximized by using the highest available contrast between n_{high} and n_{low} [15].

$$R = [\frac{n_{high} - n_{low}}{n_{high} + n_{low}}]^2. \tag{3}$$

By taking advantage of extremely low refractive index values, nanoporous coatings offer a greater refractive index contrast and thus higher available reflection coefficients than traditional non-porous layers. Second, in contrast to non-tunable refractive index layers, nanoporous layers allow *all* refractive index values between n_{high} and n_{low} to be utilized. These two advantages, high refractive-index contrast, and tunable refractive index, allow significantly better spectral control in optical interference filters. These calculations show that for filters consisting of any number of layers and any allowed maximum average reflectance value, interference filters that utilize low-*n* and tailored refractive index layers are able to achieve a higher correlation to the desired output spectra than filters that utilize non-tunable layers.

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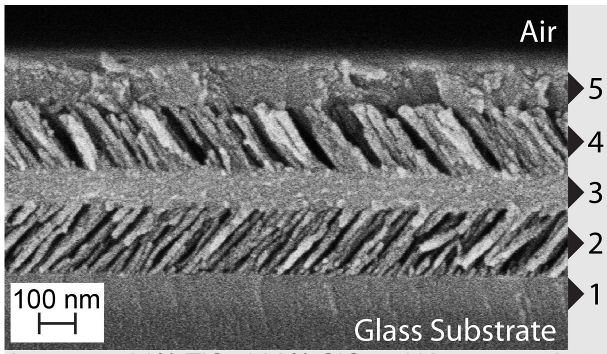
An optimized 5-layer optical interference filter utilizing tunable refractive index layers is designed and fabricated. Using a genetic algorithm, a 5-layer filter is optimized for use with an input spectrum from a Xenon-lamp at normal incidence, with a desired output spectrum that has a high correlation to the AM0 solar spectra. No limits were placed on the allowed reflectance values of the filter. The refractive index boundaries were chosen to be between n_{high} = 2.54 (TiO_2), and n_{low} = 1.10 (highly nanoporous SiO_2). The solar wavelength range considered is 400 – 1600 nm. The 5-layer filter, deposited on a glass substrate, is experimentally realized using sputtering for TiO_2 layers 1 and 3, and oblique-angle deposition of nanoporous SiO_2 layers 2 and 4. Layer 5 was deposited by co-sputtering TiO_2/SiO_2 simultaneously. An SEM image of the 5-layer filter along with layer specifications is shown in Fig. 2.



Layer 5	61% TiO_2 / 39% SiO_2	119 nm	n = 2.54
Layer 4	52% porous SiO_2	215 nm	1.10
Layer 3	TiO_2	119 nm	2.54
Layer 2	77% porous SiO_2	250 nm	1.23
Layer 1	TiO_2	101 nm	2.18

Fig. 2. SEM of a 5-layer optical interference structure for use with a Xenon lamp spectrum that utilizes tunable refractive index layers and has an output spectrum with a high correlation to the AM0 solar spectrum.

Deposition angles for the nanoporous SiO_2 are 80 and 75° for the 77 and 52% porous layers, respectively [11]. Film thicknesses and refractive index values are characterized using variable angle spectroscopic ellipsometry. The performance of the 5-layer filter's reflectance and transmittance characteristics are measured using a normal incidence broadband white light source and an optical spectrum analyzer. Figure 3 shows reflectance for this 5-layer structure as a function of wavelength, for both calculation and experimental measurement. Excellent agreement is found between the calculated and measured reflectance spectra of the 5-layer filter.

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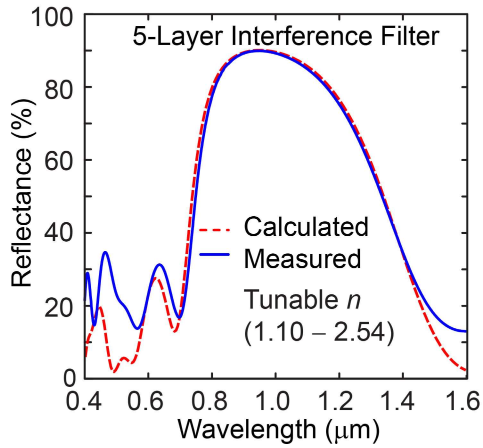

Fig. 3. Measured and calculated reflectance of the 5-layer optical interference filter plotted as a function of wavelength.

Finally, the spectral transmittance of a Xenon-lamp through the 5-layer filter is tested. In Fig. 4(a) shows (i) the original un-filtered, measured spectral intensity of a broadband Xenon-lamp, (ii) the measured spectrum after transmittance through the 5-layer optical interference filter, and (iii) the desired AM0 solar spectrum.

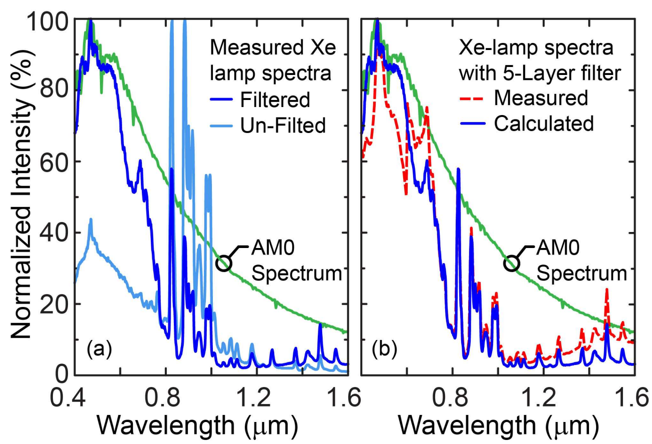

Fig. 4. (a) Measured filtered and un-filtered Xenon-lamp spectra transmitted through the 5-layer optical interference filter utilizing tailored refractive indices is compared to the AM0 solar spectrum. (b) Calculated and measured intensity of Xenon-lamp spectra transmitted through the 5-layer optical interference filter are compared to the AM0 spectrum.

It is observed that the large characteristic Xenon peaks are significantly reduced while maintaining strong correlation to the AM0 solar spectra. Excellent agreement between the calculated and measured transmittance spectra of the 5-layer filter is shown in Fig. 4(b) which plots both the measured and calculated transmittance of the filtered Xenon-lamp spectra after passing through the 5-layer optical interference coating. Using Eq. (1), the measured filtered Xenon-lamp spectrum is found to have a 0.94 correlation to the AM0 spectra as compared to 0.60 for the unfiltered source.

In conclusion we compare optical interference filters fabricated with tunable refractive index layers to filters made with non-tunable refractive index layers for a wide variety of allowed reflectance's and layer numbers. A 5-layer optical interference filter fabricated utilizing tailorable refractive index layers is experimentally demonstrated. The 5-layer filter is designed for use with a Xenon lamp that is filtered to replicate the AM0 solar spectrum with high fidelity. The measured output spectrum of this 5-layer filter is shown to have high correlation with the desired AM0 solar spectra. Optical interference filters which utilize tailorable refractive index layers have two properties that allow them to significantly outperform the transmittance characteristics of optical filters using non-tunable refractive index layers: Firstly, the refractive index of each layer maybe tuned to virtually *any* refractive index value allowing for greater flexibility in spectral response considerations. Secondly, these tailorable refractive index layers offer larger refractive-index contrasts than traditional bulk materials thereby allowing for higher reflection coefficients and/or fewer layer numbers. Such tailorable optical interference coatings have numerous and varied applications, and as the performance requirements for these optical devices continues to increase, the ability to attain greater control of spectral response is a welcome addition to the set of technological capabilities.

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