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Designing Metallic Neutral Density Filters with Constant Optical Density Versus Wavelength

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Abstract
Observations in space and on earth can be subject to wide dynamic ranges of light levels which may need to be controlled by neutral density filters. The optical density (OD) of neutral density (ND) filters made with single metal layers is often not very neutral or constant in OD versus wavelength over the wavelength band of interest. Photographers are the major users of quantities of ND filters, but there are many other applications for smaller numbers of ND filters. There are a limited number of publications on how to design metallic ND filters. It is shown here that designs of metal-dielectric-metal (MDM) can be designed to have more constant OD over a wavelength band. Designs are shown employing software which accommodates the fact that the indices of thin metal films usually vary with film thickness.

1. Introduction
A literature search for designing ND filters only came up with eight references that were closely related. There are several possibilities to create an ND filter [1-8]. A glass can be used which absorbs the light, such as provided by the colored filter glass providers such as Schott and Hoya. A high-reflecting/low-transmitting stack of all-dielectric layers can be used to make an ND filter. Thin films of metals are commonly used to make ND filters. Combination of these three basic options is also possible. Metallic ND filters are the subject of this paper. Common metallic ND filters are made with pure metals and also alloys such as Inconel (Ni, Cr, Fe), Nichrome (Ni, Cr), and Chromium (Cr). The OD of single metal layers of these materials vary somewhat with wavelength as reported by Amotchkina, et al [9].

The paper by Goodell, Coulter, and Johnson characterized the n and k of Inconel 600 (75.31% Ni, 15.54% Cr, 7.71% Fe) in layers of 22, 37.3, and 62.5 nm from 331 to 1923 nm wavelength [1]. Their data is used in the results of the present work. Index values versus thickness were also available from projects with which the author has been associated for Nichrome and Chrome in thicknesses that had some residual transmittance. These three sets of materials are used in this discussion and their indices at measured thicknesses are plotted in Figs. 1-3.

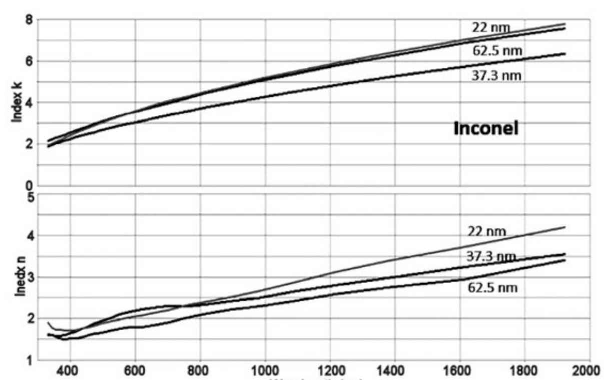


Figure 1: Measured Indices of Refraction for Inconel 600

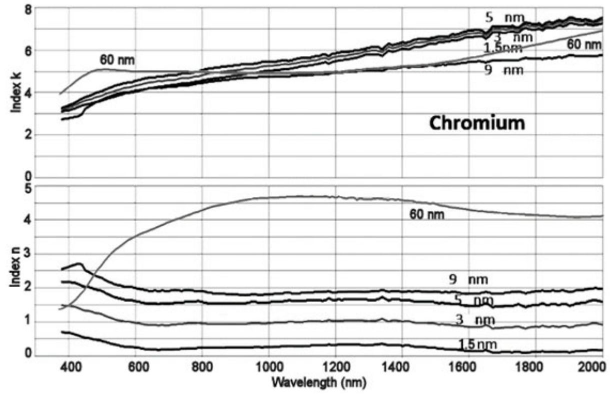


Figure 2: Measured Indices of Refraction for Chromium

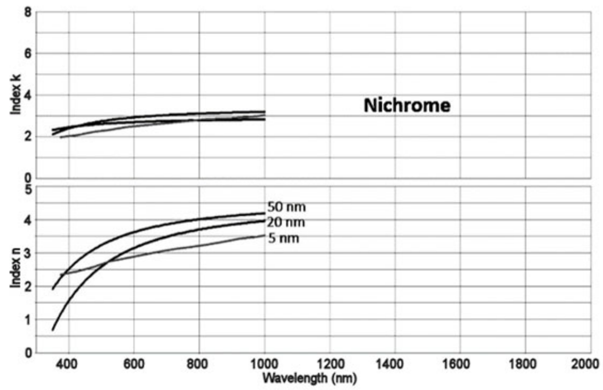


Figure 3: Measured Indices of Refraction for Nichrome

Shibukawa explored the approach of co-evaporating silver and silica to provide a ceramet with a percentage composition which would provide nearly the same OD versus wavelength in the 1-to-2.5-micron wavelength region. With a 56% volume composition, he could get any OD from 0 to 2.3 with a reasonably flat spectral response just by depositing the right thickness film of the mixture. Cushing and Simons addressed the problem of the reflections from the filter which would cause errors due to the multiple internal reflections when two or more ND filters were stacked to provide higher OD. They antireflected the ND filters to reduce this problem [2,3].

Bittar and White did similar things to that of the work of Shibukawa, but for the ultraviolet range of 200 to 800 nm using metals like Ni or Pt and SiO_2 in a ceramet [4].

Kaplan, et al. worked with metallic ND filters deposited on ultrathin substrates of Lexan. This was to avoid the spectral ripples or etaloning caused by second surface reflections of thicker substrates in FT-IR spectrophotometers and laser measurements [5].

Frenkel and Zhang performed work that is most closely related to that of this report for the 2–25-micron spectral region [6]. They emphasize the non-uniformity of OD with wavelength problem. They also mention that some materials "are strongly dependent on film thickness, and their behavior is much different from that of bulk materials." They also focused on the etaloning effects studied by Kaplan, et al. [5]. To get flat OD versus wavelenght response, they combined metals like gold and nichrome, gold and vanadium, and nichrome and palladium. However, they did not employ the MDM approach reported here. Zhang, Hanssen, and Datla demonstrated measuring down to OD 6 in the infrared using ND and other filters. Sullivan and Byrt used metal/dielectric filters and described how to protect silver from oxidation.

2. Interpolating Indices Versus Wavelength and Thickness

The variation of indices with thickness mentioned by Frenkel and Zhang has been the thrust of our work reported in recent years [10,11]. Indices versus wavelength are measured on samples prepared at several thicknesses in the spectral range and thickness range of interest. For example, Goodell, et al. measured layers of Inconel of 22, 37.3, and 62.5 nm thickness from 331 to 1923 nm wavelength. The chromium of the project with which I was associated was measured at 1.5, 3, 5, 9, and 60 nm thickness from 380 to 2000 nm wavelength. Nichrome was measured at 5, 20, and 50 nm thickness from 350 to 1000 nm wavelength. These plots of indices are shown in Figs. 1-3.

The software reported in Refs. 9 and 10 interpolates between the measured spectra for any thickness desired as the design process optimizes the parameters with respect to target goals of OD or other parameters. Figures 4-6 show the interpolated indices in 5 nm increments for each of these three materials using that software. Figures 7-9 show the OD versus wavelength that single layers of these three materials could generate in increments of 5 nm. The OD is more constant with wavelength at some layer thicknesses, depending on the material as seen in Figs. 7-9. It will be shown below that the OD plot can be made more constant at any OD by a MDM design, and the two metal layers might be different metals to give the best results.

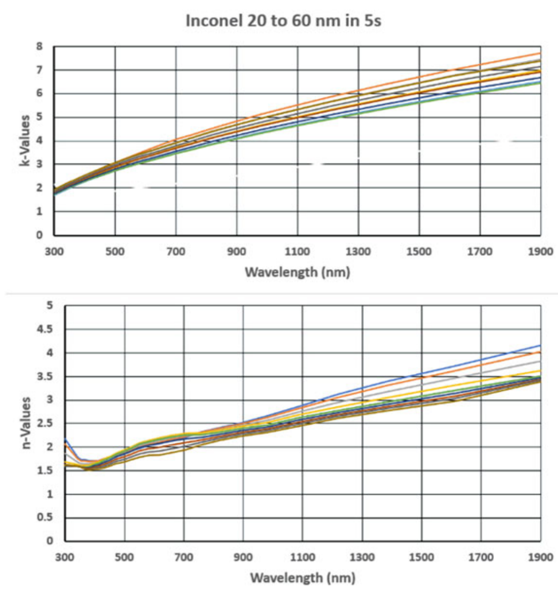


Figure 4: Interpolated Indices of Refraction for Inconel 600 from 20 to 60 nm in Increments of 5 nm

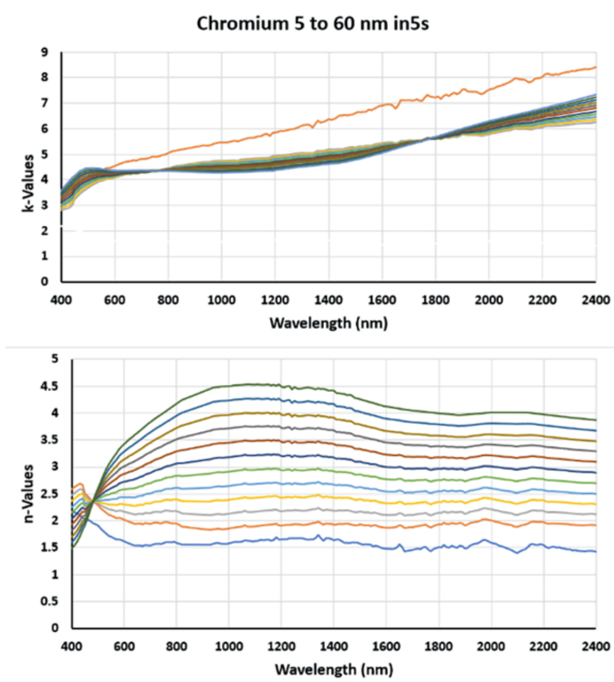


Figure 5: Interpolated Indices of Refraction for Chromium from 5 to 60 nm in Increments of 5 nm

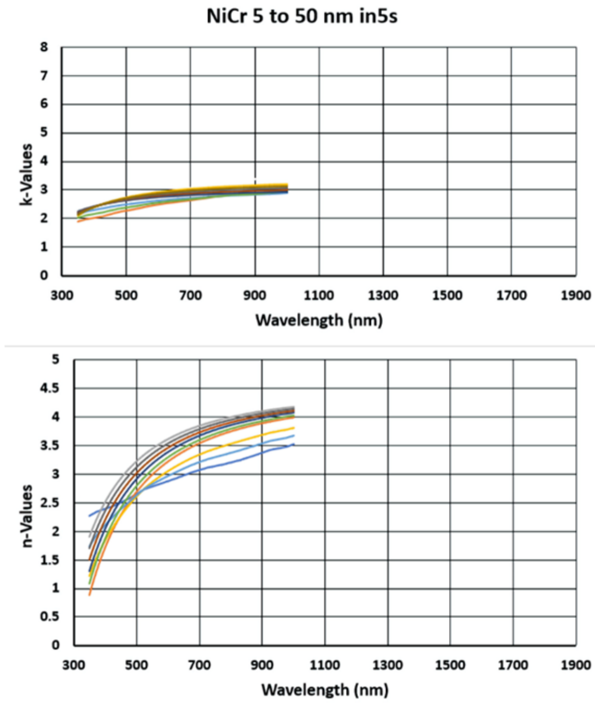
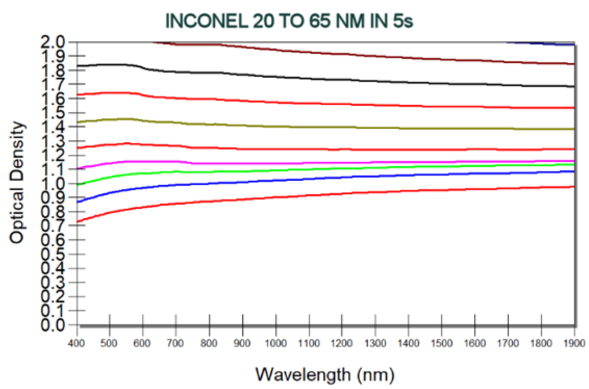


Figure 6: Interpolated Indices of Refraction of NiCr



From 5 to 50 nm in increments of 5 nm

Figure 7: OD of Inconel 600 in Thickness of 20 to 65 nm in Increments if 5 nm

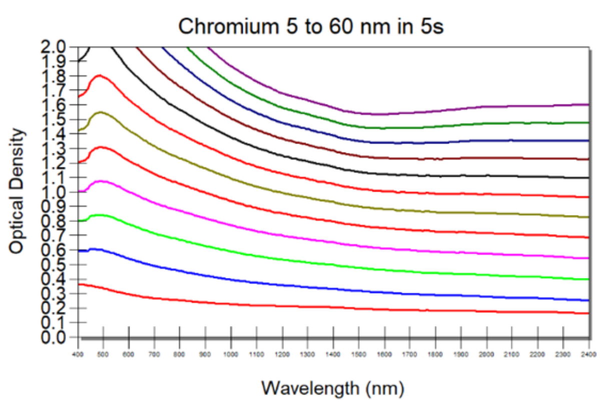


Figure 8: OD of Chromium in Thickness of 5 to 60 nm in Increments if 5 nm

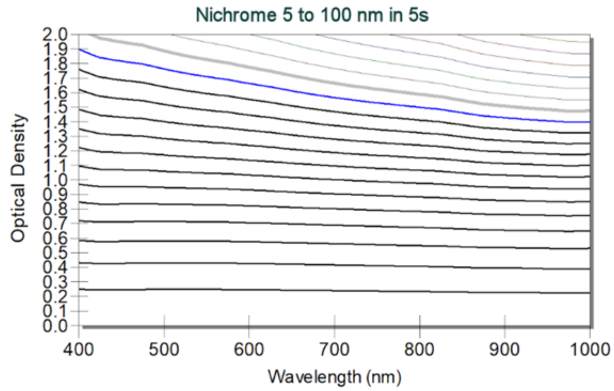


Figure 9: OD of Nichrome in Thickness of 5 to 100 nm in Increments if 5 nm

3. Design Optimization Results

Figure 10 compares the four best of the MDM designs tested using each of the three materials in the two positions of the first and last layers of the MDM configuration to make an OD1 filter from 400 to 1000 nm with minimum average deviation from an OD of 1.0. The design is of 28.48 nm Inconel, 103.55 nm Silica and 1.64 nm Nichrome gives the best result.

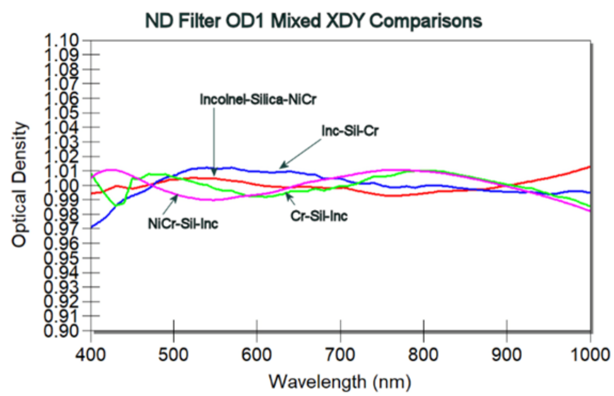


Figure 10: OD1 MDM Filter Designs with Using the Interpolating Software with the Different Material Combinations on an Expanded OD Scale

Figure 11 compares the four best of the MDM designs to make an OD2 filter with minimum average deviation from an OD of 2.0. The best material for the third layer in this case and Figs. 12 and 13 is chromium. This design is of 58.95 nm Inconel, 73.86 nm Silica and 2.87 nm Chrome.

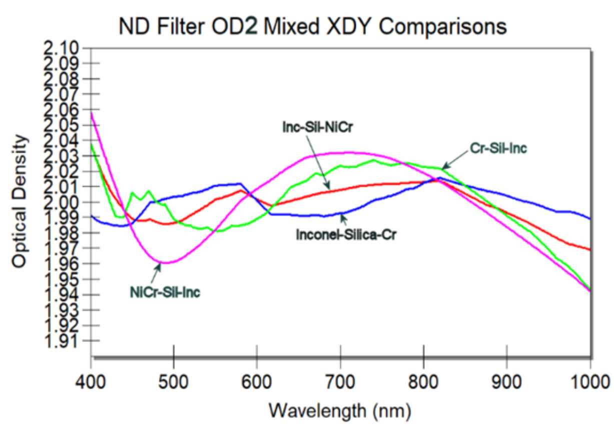


Figure 11: OD2 MDM Filter Designs with Using the Interpolating Software with the Different Material Combinations on an Expanded OD Scale

Figure 12 compares the four best of the MDM designs to make an OD3 filter with minimum average deviation from an OD of 3.0. This design is of 82.63 nm Inconel, 114.41 nm Silica and 6.53 nm Chrome.

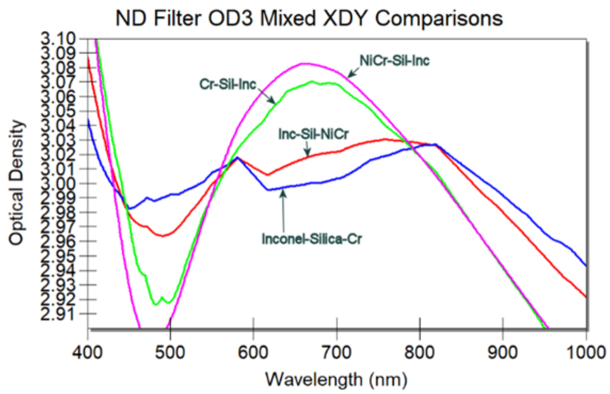


Figure 12: OD3 MDM Filter Designs with Using the Interpolating Software with the Different Material Combinations on an Expanded OD Scale

Figure 13 compares the four best of the MDM designs to make an OD4 filter with minimum average deviation from an OD of 4.0. This design is of 107.46 nm Inconel, 125.82 nm Silica and 11.68 nm Chrome.

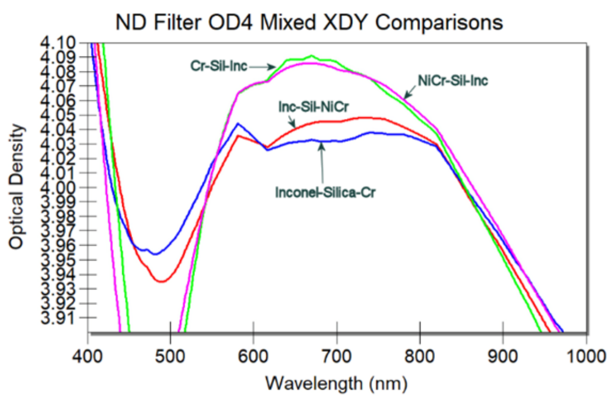


Figure 13: OD4 MDM Filter Designs with Using the Interpolating Software with the Different Material Combinations on an Expanded OD Scale

These four ND filters are plotted on the same graph of OD in Fig. 14 which emphasizes how constant (flat) the OD of these designs are with wavelength.

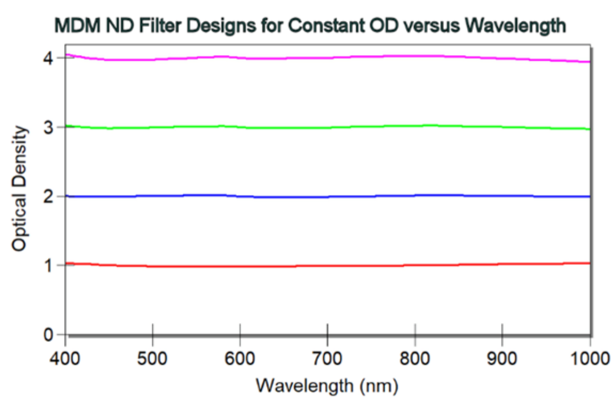


Figure 14: The Constancy of OD with Wavelength for MDM Designs of OD from 1 to 4 Using Mixed Metals and Software which Deals with the Variation of Index with Thickness

4. Conclusions

It has been demonstrated that ND filters can be designed with a more constant OD with wavelength (flatter) in the 400 to 1000 nm wavelength band by using three materials in a MDM configuration. These designs have been expedited by using software which interpolates between measured values of indices of refraction versus wavelength to use indices in thicknesses that have not been measured in the design optimization process.

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