Investigating of the Optical Properties of Rugate Filter Stacked Formulas by Using Different Materials

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ABSTRACT

In this paper, the optical properties of the multilayer rugate filter by structure of (HL) \(^9\)H has been investigated. Here the reflection, optical density and electric field strength of designed filter by using four materials of Ta\(_2\)O\(_5\), Nb\(_2\)O\(_5\) and ZnS as the materials with high refractive index and SiO\(_2\) as a material with low refractive index are compared with each other. Finally, it is realized that the bandwidth of the reflection and the optical density of the structures (ZrO\(_2\)-SiO\(_2\)) \(^9\)ZrO\(_2\), (Nb\(_2\)O\(_5\)-SiO\(_2\)) \(^9\)Nb\(_2\)O\(_5\), (Ta\(_2\)O\(_5\)-SiO\(_2\)) \(^9\)Ta\(_2\)O\(_5\) and (TiO\(_2\)-SiO\(_2\)) \(^9\)TiO\(_2\) increase respectively and the electric field strength reduces.

KEYWORDS: Rugate filter, Optical density, Reflection, Electric field, Refractive index

INTRODUCTION

The word rugate comes from the elementary shape of these filters, which is corrugated or wavy [1]. More precisely, a rugate filter is an interference coating consisting of one or multiple layers within which refractive index versus thickness profile is derived from sine or cosine functions, being of continuously varying value. This structure allows fabrication of reflective mirrors (notch filters) without the harmonic bands which are sometimes annoying in multilayer quarter wavelength filters [2], the rugate filter, as a special kind of graded refractive-index film, has continuously periodical modulation in the refractive index profile along the stack axis. Compared with a traditional filter, such a filter exhibits many advantages, such as a higher laser induced damage threshold [3] smaller sensitivity to angle variation of incident light [4] suppression of higher frequency harmonics,[5,6] smaller residual stress [6] and higher temperature stability [7]. However, preparation of the rugate filter is relatively difficult because of the requirement for accuracy in realizing the continuous refractive index profile. The filter can be fabricated by mixing two or more materials with high and low refractive indices [8-10] or by varying the content of the reactive gas with a single source [11, 12]. The electrochemical etching of silicon [13] and the glancing angle deposition [14, 15] are also used to make porous rugate filters.

Theory

A rugate filter consists of a sinusoidal refractive index deposited on a substrate [16, 17] and takes its name from the Latin word "rugate", meaning to be wrinkled or creased [16]. This profile is periodic and continuous throughout the structure of the coating. This refractive index profile is given by:

\[ n = n_a + \frac{n_p}{2} \sin\left(\frac{2\pi x}{n_a P} + \varphi_0\right) \]  

\(n_a\) is the average refractive index used, \(n_p\) is the peak-to-peak refractive index difference, \(n_a P\) is the period of the sine wave in optical thickness, \(\varphi_0\) is the phase at the substrate [rad], \(N\) is the number of sine wave cycles, and \(x\) is the spatial variable. The center of the reflection band \(\lambda_0\) is given by [17]:

\[ \lambda_0 = 2n_a P \]  

And the bandwidth of the filter \(\Delta \lambda\) is related to the other variables by [16]:

\[ \frac{\Delta \lambda}{\lambda_0} = \frac{n_p}{2n_a} \]
Finally, given the condition that \( n_p \) is small in comparison with \( n_o \) the maximum reflectance at the center of the reflection band is given by [16]:

\[
R_{\text{max}} = \tanh^2 \left( \frac{\pi n_p N}{4n_o \cos \theta} \right) \text{ for s-wave} \quad (4)
\]

\[
R_{\text{max}} = \tanh^2 \left( \frac{\pi n_p N \cos 2\theta}{4n_o \cos \theta} \right) \text{ for p-wave} \quad (5)
\]

\( \theta \) - the propagation direction in the rugate filter related to the angle of incidence 90 on the filter and the refractive index of the medium of incidence \( n_0 \) by Snell's law or:

\[
\frac{\sin \theta_0}{\sin \theta} = \frac{n_a}{n_o} \quad (6)
\]

In order to suppress the side lobes, we add the matching Eq. (9) and the apodizing function Eq. (8) to the refractive index profile Eq. (7), as shown in Fig. 1. The quantic matching layers at the substrate and the ambient medium sides are both 1 \( \mu \)m thick, and the refractive index varies from 1.52 to 1.92 [18].

\[
n(x) = n_a + \frac{1}{2} n_p f(x) \sin \left( \frac{4\pi x}{\lambda_0} \right) \quad (7)
\]

\[
f(x) = 10x^3 - 15x^4 + 6x^5 \quad (8)
\]

\[
n(x) = n_s + (n_a - n_s)(10x^3 - 15x^4 + 6x^5) \quad (9)
\]

In order to design this filter we use \( \lambda_0 = 532 \) nm, \( n_a = 1.75 \), \( n_p = 0.35 \), and \( n_s = 1.5 \).

**Designing method of Rugate filter by using different materials**

Optical interference filters are usually made by deposition of separated layers of materials with different indices of refraction. A simple rugate filter can be made by deposition of layers by high and low refractive index with a thickness of a quarter of wavelengths that have been deposited periodically.

Here the formula has been used for dielectric multi-layer stacked structures of the rugate filter is \((HL)^m H\), where \( m \) is an integer and the number of courses. We considered the 19-layer structure of \((HL)^9 H\) and we used four materials such as Ta\(_2\)O\(_5\), Nb\(_2\)O\(_5\), ZnS,TiO\(_2\) as high refractive index \( n_H \) and SiO\(_2\) as low refractive index layer \( n_L \) in visible region.

In this simulation, the incident wavelength is considered 532 nm and white is selected as lighting. Air with \( n = 1.0 \) is considered as landing environment and glass with \( n = 1.52 \) as the substrate and the exit environment and detector is assumed ideal and broadband.

In this section, ZrO\(_2\) with a refractive index of \( n = 2.22 \), Nb\(_2\)O\(_5\) with the refractive index of \( n = 2.33 \), Ta\(_2\)O\(_5\) with the refractive index of \( n = 2.42 \), TiO\(_2\) with the refractive index of \( n = 2.28 \) are materials as high refractive index and SiO\(_2\) with \( n = 1.46 \) as the low refractive index are considered for 19-layer of \((HL)^9 H\) in the visible structure of \( n_L \). Here the reflective charts, optical density, electric field strength of every material of each structure are calculated and checked.
Optical density characterizes the attenuation of performance of a filter and it is always expressed as the negative of transmission logarithm:

\[ OD = -\log_{10}(T) \] (10)

In Fig. 3, the optical density of this 19 layers filter according to the wavelength is plotted and in Fig. 4, the diagram of distribution of Electric field intensity for per layer in the central wave length of 532 nm has been plotted [19]. As it is seen, the bandwidth of the reflection and the optical density of the structures (ZrO\textsubscript{2}-SiO\textsubscript{2}) \textsuperscript{9}ZrO\textsubscript{2}, (Nb\textsubscript{2}O\textsubscript{5}-SiO\textsubscript{2}) \textsuperscript{9}Nb\textsubscript{2}O\textsubscript{5}, (Ta\textsubscript{2}O\textsubscript{5}-SiO\textsubscript{2}) \textsuperscript{9}Ta\textsubscript{2}O\textsubscript{5} and (TiO\textsubscript{2}-SiO\textsubscript{2}) \textsuperscript{9}TiO\textsubscript{2} increase and the electric field strength reduces.
Conclusion

A rugate Filter is an example of multilayer Filters that the absorption of heat caused by radiation in each point is proportional to the electric field strength at the same point. For the structures of \(\text{ZrO}_2\text{SiO}_2\) \(\times 9\text{ZrO}_2\), \(\text{Nb}_2\text{O}_5\text{SiO}_2\) \(\times \text{Nb}_2\text{O}_5\), \(\text{Ta}_2\text{O}_5\text{SiO}_2\) \(\times 9\text{Ta}_2\text{O}_5\) and \(\text{Ti}_2\text{O}_5\text{SiO}_2\) \(\times 9\text{Ti}_2\text{O}_5\) the reflective bandwidth and optical density increase via refractive index difference in \(\text{ZrO}_2\), \(\text{Nb}_2\text{O}_5\), \(\text{Ta}_2\text{O}_5\) \(\text{TiO}_2\) and \(\text{SiO}_2\), but the maximum and minimum of electric field strength reduces by increasing the refractive index difference of material; and the intensity of the electric field is also reduced to zero in the lower layers. Filters by High optical density are useful for expanding the dynamic area of detector systems and reducing the output current of laser. The electric field strength in the mentioned rugate filter reduces which it causes to reduce the laser damage threshold in materials and available components. It fundamentally affects on costing, designing, and operation of large laser systems.

REFERENCES


