# Graded Period Rugates

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## Abstract

Grading the refractive index period of a rugate is a technique for depositing broad band reflectors using rugate technology. The principle advantage of this technique is the ability to deposit long and short pass reflectors in parallel with other rugate spectral features and thus generate complex performance in a single optical film. Variation of the amplitude of the index profile as the period is changed allows for good edge definition for long or short pass designs. Several of these devices were fabricated and measured performance is presented. These devices demonstrate rugate properties of harmonic suppression and superposition with other rugate structures.

## 1. Introduction

Rugate filters are optical interference films in which the refractive index of the film varies continuously and periodically as a function of deposited optical thickness. In the example of a single narrow band reflector, the refractive index (n) of the film at an optical thickness (i) is:

$$n(i)=amp(\sin(4\pi i/\lambda+\theta))+n_{ave};$$

where: amp is the index amplitude, $\lambda$ is the center wavelength of the desired reflection notch in the same units as (i), and $n_{ave}$ is the effective average index of the film.

Bandwidth (BW) of the rugate reflection notch is a function of the amplitude of the refractive index profile and the average index of the film and is approximately(1):

$$BW=amp/n_{ave};$$

Figure 1 illustrates the relationship of refractive index amplitude and period to film performance for a single reflection notch rugate. The refractive index of the rugate varies continuously while a discrete stack consists of alternating layers of two materials of different refractive index. Figures 2a and 2b present measured sprectral performance for a single reflection notch, short pass, rugate. This device defines the long wavelength cutoff for a hyperspectral imaging spectrophotometer. High transmission between 0.4 and 2.5 microns is a system requirement. The lack of reflection bands at harmonic positions in the rugate spectra is a characteristic performance difference between rugate and discrete filter designs.

A powerful design advantage of rugate technology that goes hand in hand with harmonic suppression is the superposition of performance achieved by superimposing individual index profiles. Figure 3 illustrates the superimposed profile of three, single reflection notch profiles. In the example of a multiple reflection band rugate, the refractive index (n) at optical thickness increment (i) is:

$$n(i)=n_{ave}+\sum_{j=1}^{nbands} amp_i(\sin(4\pi i/\lambda_j))$$

where: *nbands* is the number of desired rugate reflection bands, and $\lambda_j$ is the wavelength of the desired $j^{th}$ reflection band.

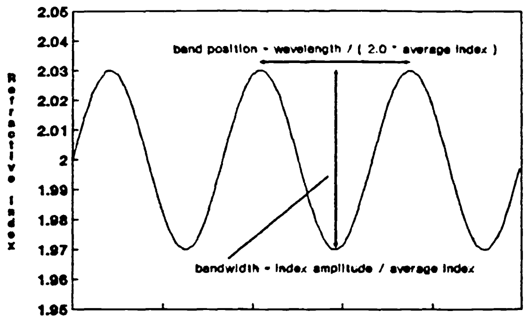


Figure 1: The refractive index profile for a single reflection notch rugate is a continuously graded and periodic function of optical thickness.

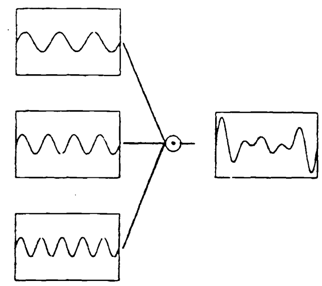

Figure 3: A rugate design advantage is the ability to build up complex spectral performance by superimposing individual index profiles. This figure illustrates the superposition of three notch reflectors.

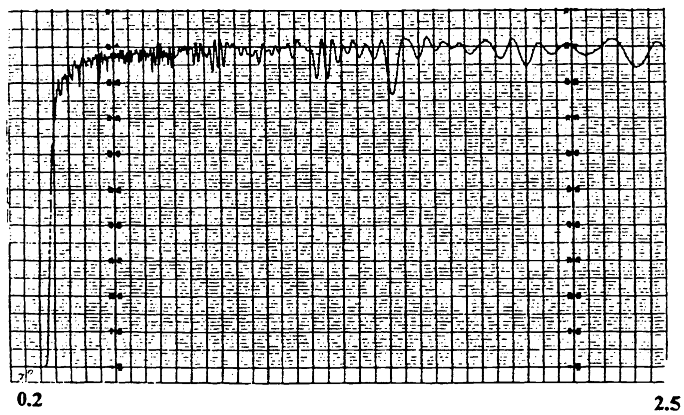


Figure 2a: Measured spectral performance from 0.2 to 2.5 microns of the single band NIR rugate shown in figure 3b illustrates the performance advantage of harmonic suppression. The filter is on $Al_2O_3$ and the second surface is uncoated.

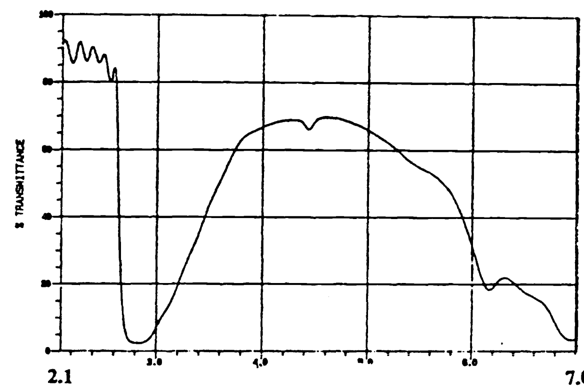


Figure 2b. Measured spectral performance from 2.0 to 7.0 microns of a NIR rugate designed as a short pass filter to define the long wavelength edge of a hyper spectral imaging spectrophotometer.

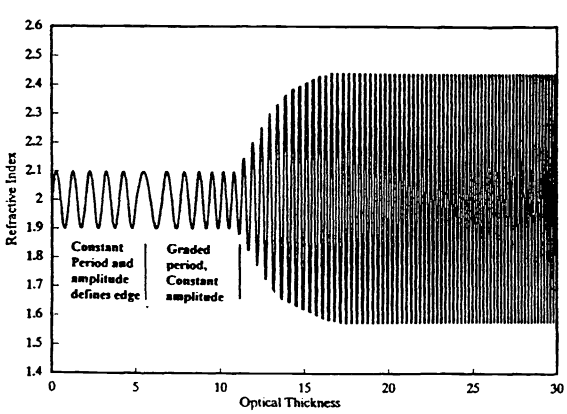


Figure 4: Exaggerated refractive index profile for a graded period rugate.

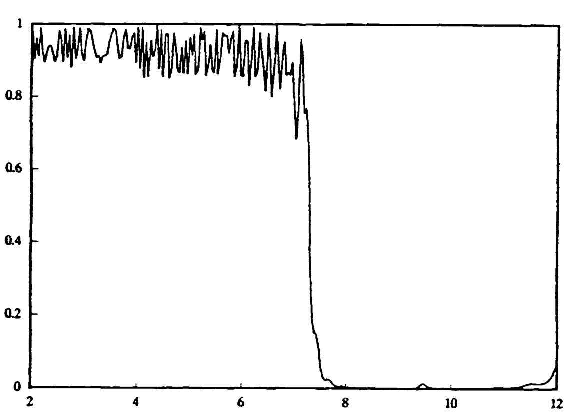


Figure 5: Predicted performance for a graded period rugate designed to reflect 8 to 12 microns and pass shorter wavelengths.

As previously discussed, the bandwidth of a constant period rugate is a function of the amplitude of the periodic index profile. An advantage of rugates is that the reflection notch is easily designed to any desired bandwidth within the practical constraints of the index excursion available from the selected film system and the controllable limits of the process. Rugates are particularly suited to narrow band reflectors. However, as the index amplitude is reduced, the number of rugate cycles or the film thickness needed to achieve a specified reflectivity must be increased. The potential design space of the film system, that is the refractive index that is not used by the narrow bandwidth rugate times the film's thickness, is available for simultaneously fabricating other spectral features.

A group technology classification study was performed to identify rugate spectral features, in addition to the narrow line reflector, that exhibit properties of orthogonal design, and are therefore easy to combine into a single rugate film without concern for interactions. Properties of orthogonal design are the previously discussed properties of harmonic suppression, superposition and limited interaction or imposed stress on the fabrication process. The goal of this study was the generation of procedures that can be superimposed to generate complex designer films using techniques and processes already in hand for fabricating narrow notch reflectors. The graded period rugate is an example of such a technique. Bandwidths broader then the index excursion of the film system or what the remaining potential design space allows is achieved by slowly changing the design wavelength of the reflection band. In this way, a broad reflection notch can be added in parallel to the narrow notch without being limited by the index excursion of the film.

## 2. Group technology classification

Group technology classification is a manufacturing science tool for understanding and organizing process technologies. Rugate technology is composed of an emerging set of design, process control and process monitoring techniques. The idea of using group technology classification is to try to better define rugate technology in terms of processes and techniques that are now well in hand and map them into application requirements. This study highlights what the technology is capable of, as well as areas that require further development. Our goal is a rugate fabrication chamber capable of rapidly designing and fabricating any sort of designer film from system specifications. This study is an ongoing method for directing our process development efforts.

Our approach to developing a classification system consists of identifying spectral features that are unique and orthogonal, evaluate methods for fabricating those features, identify cost and performance advantages as well as drivers and lastly to map these features into general application classes. Unique and orthogonal spectral features are those which can be fabricated in parallel with little consideration to interactions or process limitations, yet require different methods of monitoring or index profile generation.

Spectral features that were identified include: narrow and broad band reflectors, broad band mirrors, narrow and broad pass bands and anti reflection films. A discussion of each of these follows.

Narrow band reflectors: A narrow band reflector is loosely defined as having a bandwidth of 10% or less. These devices have driven rugate development to date. Attributes include fine control and flexible placement of single or multiple reflection notches and the absence of harmonics. The principle method of fabrication consists of the deposition of a continuously varying index profile. Multiple index profiles are summed for multiple reflection notches. Control of line position and index amplitude stresses process and insitu monitoring. Performance uniformity across the part is critical. For multiple notch index profiles, high slew rates cause lead and lag errors that can give rise to unwanted performance digs at beat frequencies of the constituent profiles.

Broad band reflectors: Broad band reflectors are single, broad band reflectors on the order of 10 to 20 % bandwidth with little or no harmonic content. These structures differ from narrow band reflectors in that the fabrication process is typically driven harder and secondary effects begin to come into play. If the index is being controlled by codepositing two materials, rate clipping at practical values is an option. A

**Rugate Coating Group Classification Coding System**

| Two Letter Application Code | Three digit Feature Code | Two digit Performance | One letter Driver Code |
|---|---|---|---|
| ☐☐ | ☐☐☐ | ☐☐ | ☐ |

**Application Code**

| | |
|---|---|
| WN | Window coatings |
| AR | Single band antireflection film |
| BA | Broad and multi band antireflection film |
| BS | Beamsplitter |
| DC | Dichroic |
| NT | Notch filters |
| BP | Bandpass |

**Feature Code - Sum Codes**

| | |
|---|---|
| 1 | Narrow Band Reflectors |
| 2 | Broad band reflectors |
| 4 | Broad band mirrors |
| 8 | Narrow bandpass |
| 16 | Long pass |
| 32 | Short pass |
| 64 | Anti-reflection |
| 128 | open |
| 256 | open |

**Performance Code - Sum Codes**

| | |
|---|---|
| 1 | Harmonic suppression |
| 2 | In-Band Transmission |
| 4 | High Optical Density |
| 8 | Narrow/Broad line |
| 32 | Multi-Performance |

**Driver Code**

| | |
|---|---|
| C | - Cost was a driver in design |
| P | - Performance was the driver |
| B | - Optimize both |

**Rugate Coating Group Classification Coding System**

| One Letter Substrate Code | One Letter High Index | One Letter Low Index | One letter Absorption | One Letter Spectral Code |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

**Substrate Codes**

| | |
|---|---|
| A | Al2O3 |
| G | Ge |
| S | Si |
| B | Bk-7 |
| Q | SiO2 |
| D | Boro Silicate |
| C | ZnS |
| Z | ZnSe |

**Material Codes**

| | |
|---|---|
| T | TH4 |
| Z | ZnSe |
| C | ZnS |
| C | CeF |
| Q | SiO2 |
| R | SiO |
| T | TiO2 |

**Spectral Region**

| | |
|---|---|
| U | Ultra Violet |
| V | Visible |
| E | Extended visible |
| N | Near IR |
| M | Mid IR |
| F | Far IR |
| I | IR |

**Absorption Codes**

| | |
|---|---|
| S | Substrate absorption edge used as part of design |
| M | Film material absorption edge used as part of design |
| N | Material absorption not a factor in design |

Figure 6: Group technology classification scheme for rugate technology. This technique inventories rugate design and process procedures

problem with rate clipping is that it introduces some harmonic content. These harmonics can be removed by adding anti-lines to the profile -- lines at the harmonic frequency but out of phase with the principle. The maximum bandwidth is limited by the practical maximum index excursion of the film system and process.

Broad band mirrors: Broad band mirrors, short and long pass reflectors require an index excursion that exceeds that which is available from the film system and design. This maybe a very broad band reflection notch or a notch that can not be made in parallel with other required spectral features. The technique suggested is the graded period rugate. The period of the rugate is slowly changed throughout the deposition.

Narrow band pass: Narrow band pass filters transmit at a narrow wavelength or set of wavelengths but have good reflection throughout the rest of the band. A narrow band pass can be generated in a number of ways. These include Fabry-Perot, graded period and with two adjacent reflectors deposited in parallel. The Fabry-Perot consists of a tuned reflector, a cavity and a tuned reflector. The graded period rugate exhibits a single transmission leak that can be wavelength tuned during the deposition. The third method is to deposit two adjacent lines in parallel where the number of cycles deposited between the two lines differs by an integer number(2) (this is a special case of the profile termination problem for multi band rugate reflectors deposited in parallel).

Broad band pass: Broad band pass filters define the transmission of the sensor band. Methods of fabrication include deposition of two lines either in series or parallel if the available index excursion permits, or depositing two, graded period rugates in which the grade for each is away from the pass band region.

Anti-reflection: Anti reflection films exhibit very low reflection at a wavelength, sensor band or multiple bands. Graded index anti-reflection films exhibit good broad band characteristics and are straight forward applications of the rugate process. They are used for improving second surface losses or for index matching the substrate and rugate as well as the rugate to entrance media.

The next step in developing a technology classification system is identification of performance and cost advantages and disadvantages. Performance advantages may or may not be required by an application. The use of previous design and cost data may not be relevant if there is an unusual cost driver or specification. Comparison of designs must take these issues into account. Performance issues include harmonic suppression, in-band transmission, high optical density, narrow, broad band, multi band or hyper spectral band performance.

The final step is the mapping of designs into relevant application classes. Examples of these classes include window coatings, single, multi and broad band anti reflection films, beam splitters, dichroics, pass bands and notch filters.

Figure 6 present the final group classification system is detail. The group code consists of two parts. The first part is an eight digit code and contains design and application information. The second part of the code is five digits and contains material and process information. The goal of designing a group classification system is to inventory designs and process information for rapid and accurate retrieval. This information will be available to a design for manufacture (DFM) expert system so that it may produce a workable index profile to meet filter specifications. In order for the system to work, a full suit of fabrication methods must be available. A missing component identified by this study was a means of fabricating broad band reflectors and this in turn lead to developing and demonstrating the graded period rugate.

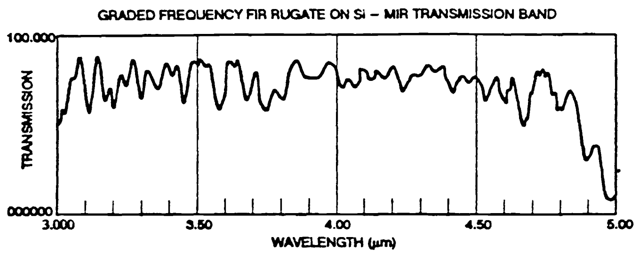


Figure 7a: Measured spectral performance from 3 to 5 microns of 8 to 12 micron graded period rugate on Si.

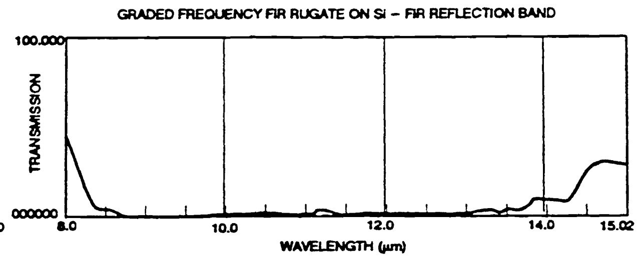


Figure 7b: Measured spectral performance from 8 to 15 microns for an 8 to 12 micron graded period long pass rugate.

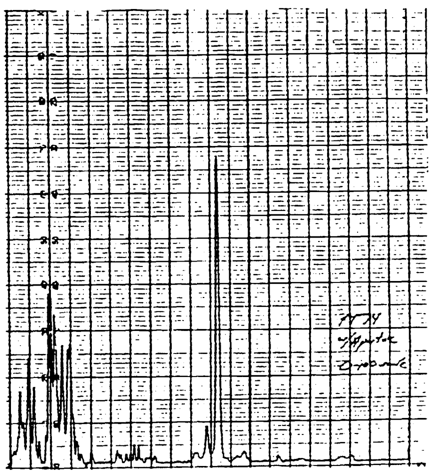

Figure 8a: Measured spectral performance from 0.4 to 2.5 microns for a 4.1 to 1.56 micron long pass graded period rugate on $Al_2O_3$.

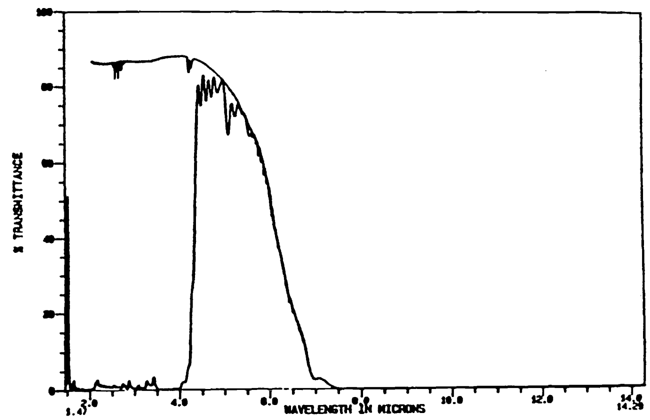


Figure 8b: Measured performance for a 4.1 to 1.56 micron long pass graded period rugate - 1.4 to 14 microns is shown. Spectral performance for uncoated $Al_2O_3$ is overlaid for reference.

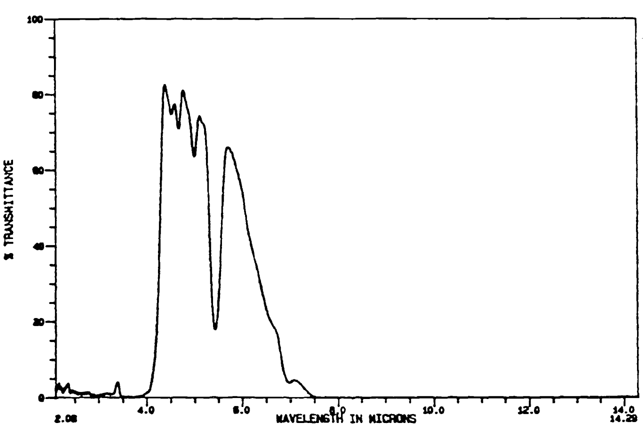


Figure 9: Measured performance for a 4.1 to NIR short pass graded period rugate codeposited with a narrow band fixed period rugate at 5.5 microns.

## 3. Examples of graded period rugates

A graded period rugate is a means of arbitrarily broadening the reflection band width. The optical thickness period of the rugate is increased or decreased continuously by a small amount. For long or short pass designs where transition edge slope is important, a rugate of low index amplitude is first deposited with the optical thickness held constant. Once the edge is defined, the period is slowly changed and the rugate is drawn away from the pass band edge. The amplitude of the rugate is increased from the low index amplitude that defined the edge to as high an index excursion as the system allows. The index amplitude and the rate at which the period is changed, control the level of optical density of the reflected region. Figure 4 presents an exaggerated refractive index profile for a graded period rugate. Figure 6 presents predicted spectral performance for a graded period rugate designed to reflect 8 to 12 microns.

Figures 7a and 7b are spectral scans of an IR rugate on silicon. The rugate period was sheared at a rate of 0.12 microns per cycle. Figure 7b shows spectral performance from 8 to 12 microns while figure 7a shows good transmission between 3 and 5 microns. The part is not anti reflection coated on the second surface.

Figure 8a and 8b are spectral scans of a second IR rugate. The edge was defined by depositing 10 cycles of a constant index amplitude of 0.1 at a design wavelength of 4.1 microns. As the rugate period was decreased by 0.04 microns towards shorter wavelengths, the index amplitude was increased to 0.3 microns. The period was graded to 1.56 microns. Two interesting features are seen in the visible/NIR scan from this filter. The first is that a narrow leak at 1.5 microns is present and the second is that good blocking is obtained at short frequencies ahead of the grading. The narrow leak is found to be tunable and moves with the leading edge of the graded period and suggests an interesting method for making a narrow band pass filter. Figure 9 is a similar graded period rugate with a single fixed period reflection notch added to the index profile. The index amplitude of the fixed period rugate was 0.03.

## 4. Summary

In summary several graded period rugates have been fabricated. They exhibit good harmonic suppression characteristics and can be combined with other rugate features. The principle advantage of the technique is seen as a way of efficiently using potential design space if broad blockig is desired and another spectral feature, such as a narrow band reflector, is required and defines the film's thickness. Group technology classification is useful in defining rugate technology and is seen as an eventual method of quickly retrieving previous design and process information and procedures for use by an expert profile generator.

## 5. Acknowledgments

Hughes Danbury Optical Systems has been developing rugate technology for several years with the support and direction of the Material Directorate of Wright Laboratory. The work presented here was executed under internal HDOS funds and builds upon our pervious work.

## 6. References

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