Application of graded-index thin film in laser attack and defense equipment

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Abstract. Laser as a weapon used in contemporary warfare has been very common. As an important part of laser weapons, thin film plays an important role in laser attack and defense equipment. The manufacturing technology of graded-index thin film has always been a focus in the field of military science and technology and one of the key technologies to promote the development of laser weapons. This paper summarizes the present domestic situation of the graded-index thin film coating, and specifically introduces the application of graded-index thin film in laser equipment.

1. Introduction
Film plays important role in laser attack and defense equipment, its quality should affect function of laser attack and defense equipment. High quality film could guarantee high energy output of laser attack and defense equipment, lower quality film should be soft spot of whole system. The graded-index thin film is also called the gradient-index thin film. The refractive index of its layer changes gradually along the normal direction of the substrate surface as the thickness of the film layer increases. The structure of the graded-index thin film is essentially different from that of the traditional optical film, the physical properties and microstructure change continuously in the longitudinal direction, and there is no mutation interface, so the film has a better performance than the traditional optical film in terms of low scattering loss and high LIDT [1-5]. Because of the characteristic of gradual change of refractive index, the film stack is more flexible than the traditional optical film, and can be used to design special spectral requirements that the traditional uniform multilayer film cannot meet [6]. Therefore, graded-index thin films are widely used in broad band anti-reflective film, absorption film of solar glass, chirped medium laser mirror and etc [7].

In this paper, the result characteristics and performance advantages of graded-index thin films are introduced, the preparation technology and process status of graded-index thin film are summarized, and the prospect of military applications is analyzed.
2. The structure of graded-index thin film

In the traditional optical film design, the film layers of high and low refractive index materials overlap alternately to form different film stack structures. Based on the principle of light interference, optical film stacks such as splitter, anti-reflection, high reflection and filter are formed. There are essential difference between the graded-index thin film and the traditional optical film. The film stack dislocation designed by Rugate theory is shown in figure 1.

![Graded-index curve](image1.png)

**Figure 1.** Graded-index curve.

The value of refractive index changes continuously with the thickness of film increasing [8-10]. Stratified equivalent theory is used to analyze the optical properties of graded-index thin film approximately, its method is to use enough uniform layers with same refractive index instead of one graded-index thin film layer [11]. The changing envelope curve of these uniform layers traced out the refractive index distribution of graded-index thin film. The graded-index thin film is divided to N child layers along the normal direction, the physical thickness of each layer is equal and their refractive index are uniform, as shown in figure 2.

![Graded-index hierarchical equivalent diagram](image2.png)

**Figure 2.** Graded-index hierarchical equivalent diagram.

The graded refractive index has the characteristics of wavelet function, which is similar to the high-frequency or low-frequency oscillation, and is simulated according to the layered equivalence theory: the low-frequency sine function is nested with the high-frequency sine function, and the graded refractive index distribution function of the thin film can be expressed as the following formula [12,13]:

\[ n(x) = \sum_{i=1}^{N} n_i \sin \left( \frac{2\pi x}{h} \right) \]
where: \( N \) is the number of rugate; \( I \) is the number of rugate subdivision; \( S \) is the number of large periods; \( i \) is the number of subdivision layers of rugate.

In addition to the graded-index thin film based on Rugate theory, there is another structural model of the graded-index thin film—periodic graded-index thin film. The periodic refractive index structure refers to that the refractive index of the odd layer (even layer) of the film layer varies, while the refractive index of the even layer (odd layer) is constant. The refractive index variation trend of this film stack is similar to that of the Rugate theory to some extent, and can be called rugate-like, as shown in figure 3.

\[
\eta = \frac{n_{hi} + n_{lo}}{2} - \frac{A(n_{hi} - n_{lo})}{2} \sin \left( \frac{2\pi i}{N} \right)
\]

(1)

\[
A = \sin \left( \frac{\theta \pi}{180} + \frac{\pi i S}{T} \right)
\]

(2)

Figure 3. Periodic graded-index bar graph.

The structural of the periodic graded-index thin film can be described as the following formula GLASS/ML(ML)(ML)...)123(ML)/AIR, Where, \( M_i \) is the variable index film layer and \( L \) is the fixed low index film layer.

The typical periodic function — sine function is used as the envelope of index change in odd layer of the periodic variable index film system for initial design. The curve of index change can be expressed by the following formula:

\[
\eta = \frac{n_{hi} + n_{lo}}{2} - \frac{n_{hi} - n_{lo}}{2} \sin \left( \theta + \frac{2i S}{N} \right) \pi
\]

(3)

Where: \( \theta \) is the initial phase; \( i \) is the sequence number of the inner sub-layer of the period; \( S \) is the number of cycles; \( N \) is the total number of layers in a single period.

Compared with traditional thin films, the main characteristic of the graded-index thin film is to reduce the effect of material interface mutation when the high and low index film layers alternate in the film stack structure. The negative effects caused by the abrupt change of interface include: first, during the coating process, great stress will occur between the layers of high and low refractive index films; second, the bonding force between film layers is not strong enough; third, at microcosmic aspect it is not easy to match high and low refractive index materials, also easy to bring film defects, increase the scattering loss, and reduce the LIDT of film. Therefore, in the application of laser attack
and defense equipment, the graded-index thin film has great advantages that the traditional optical film does not have, because it does not have the material interface in the strict sense. Flexible film structure design is also a great advantage of graded-index thin films, which can bring a new design direction, qualitative leap in performance.

3. Preparation technology of graded-index thin film
The preparation technology of graded-index thin film is one of the keys to develop laser attack and defense equipment. For many years, many coating researchers have been seeking technology for the preparation of high precision graded-index thin films.

According to its preparation principle, the following methods are common: first, the multiple method, depositing two or more different film materials to the substrate at the same time. The gradient of refractive index is achieved by changing the deposition proportion. Such as multi-source co-evaporation method, target co-sputtering method and, etc [14-17]. The second is the reactive deposition method, which uses the different partial pressures of the reactive gas or sputtering gas during the coating process to bring about the gradual change of refractive index. Such as magnetron reactive sputtering method and PECVD method [18]. The third is the deposition parameter changing method, which can change the refractive index by changing the deposition temperature, air pressure changing and deposition angle changing, such as oblique incidence deposition method [19].

A practical method for preparing graded-index thin films is to mix two or more different index materials to obtain a monolayer with any index in the middle, and then to prepare characteristic films for specific spectral requirements [17]. How to obtain a monolayer with any middle refractive index is the real difficulty in the process of graded-index thin film coating. In order to achieve this, the key is to ensure that the components of the film materials are mixed in a stable manner according to the expected proportion, so the refractive index is controllable during the preparation process.

Some domestic universities and research institutes have conducted several studies on this subject, such as: Ning Xiao-yang and others carried out the "Research the Deposition of SiO2/TiO2 Nonlinear Refractive-index Optical Thin Films", used electron gun monophyletic mixed evaporating technology, evaporated separately the mixture of SiO2/TiO2 in 1:1 and 1:2 ratio, studied and analyzed the change of the refractive index, and compared with evaporating method with double source. From the result, film material mixture ratio dose not relate to refractive index of graded-index thin film, the method using electron gun monophyletic mixed evaporating to achieve coating with high accuracy is feasible poorly [16]. In 2004, Shen Zi-cai et al. studied various preparation methods of graded-index thin film. By changing the oxygen flow rate or sputtering power, the refractive index of silicon oxide prepared at the wavelength of 1550nm changed from 1.44 (SiO2) to 3.69 (Si), and single-wavelength notch filters were prepared simply [20]. Using OTFS1650 of OPTORUN developed a coating technology for preparing Nb,SiOx graded-index filter by Cheng Xin-bin [18]. The method can accurately prepare Nb,SiOx films with any refractive index between 1.517 and 2.219 (600nm). Qiao Zhao and Ma Ping et al. prepared the graded-index high reflective film based on high LIDT [17]. The experiment designed the film with the film stack optimization software Spektrum32, and did on Navigator1000 of CEC with broadband spectrum monitoring, obtained an any refractive index material between SiO2 and Ta2O5 with sputtering elemental silicon/tantalum dual splicing target by the single ion beam and
feeding oxygen to the chamber to make react between oxygen and atom out of target, prepared graded-index high reflective film successfully in 1064nm.

Combined with the existing experience, from the perspective of the preparation technology, the target material co-sputtering method is more advantageous in the exact preparation of the graded-index thin film because its deposition ratio of the film is easy to control and the method of obtaining the intermediate any refractive index film is direct and reliable. Ion beam deposition is also unique among various methods for preparing graded-index thin film, because it improves the migration force of the deposited molecules or atoms, thus increasing the film packing density, reducing the interspace of the film and reducing the scattering loss of the film [21]. In conclusion, ion beam sputtering can combine the advantages of target sputtering and ion beam deposition. Although it is difficult to carry out, it is more feasible for the preparation of high-precision graded-index thin films.

In addition, in order to obtain high-precision graded-index thin films, developing the graded-index thin film stack design software that can be connected with the equipment is also crucial.

4. Typical applications of graded-index thin films
Thin film directly affects the performance of laser system. Therefore, high quality optical thin film is indispensable for laser attack and defense equipment.

4.1. Graded-index high reflective films and their typical applications
High reflectivity film is a typical film stack in mult-layer films. The graded-index high reflective film is the High reflectivity film obtained by using the graded-index thin film designing method and preparation process, as shown in figure 4.

![Figure 4. High reflective film.](image)

An innovative application of high refractive index film is to provide high quality laser refractive mirrors. The laser is the chief component of the laser attack and defense equipment, which generally includes a resonator with two mirrors, as shown in figure 5.
One mirror requires the highest possible reflectivity, and the other, as an output mirror, can pass through the laser beam in a limited way. The loss (absorption and scattering except reflection) is required to be as low as possible [21,22]. A high reflector is usually obtained by coating the lens with a high reflectivity film of a certain wavelength that is infinitely close to 100%, while an output lens is obtained by coating the lens with a beam splitter film of the same wavelength.

Improving the reflectivity of the laser mirror is one of the methods to increase the output power of the laser. The higher the reflectivity of the laser reflector, the higher the quality factor value in the plane parallel resonator of the laser. Increasing the reflectivity by another 0.01% even if the reflectivity is 99.9% also contributes greatly to the output power. From the perspective of traditional high reflectivity film stack design, the reflectivity can approach to 100% infinitely as long as the number of film layers is increased. But in fact, due to the absorption and scattering loss in the film layer and the intrinsic absorption of the film material itself, when the film layers reaches a certain number, continued coating cannot improve its reflectivity, otherwise it will decrease its reflectivity because of the absorption and scattering loss. First, because it reduces the effect of the interface alternations between high and low refractive index mutations, the film defects caused by the matching of high and low refractive index materials will be greatly reduced and the scattering loss will be reduced. Second, the gradient change of refractive index can replace many materials lacking in the traditional optical thin film design, making the film stack more controllable and making up for the reflectivity decreasing caused by the intrinsic absorption of materials in a way [23].

Increasing LIDT of the laser mirror is another way to increase the output power of the laser. In the laser damage study of traditional high reflectivity film, the effect of interfacial absorption is as important as that of material absorption. For the interface between film layers: due to the alternating deposition of high and low refractive index materials during the preparation process, the impurity concentration at the interface is higher than that in the film body. This is an important factor influencing the laser damage of high reflectivity film. However, the graded-index high reflective film has the common characteristics of the graded-index thin film, that is, there is no alternating deposition interface of high and low refractive index material in the strict sense. Therefore, it overcomes the instability, poor adhesive force and large stress caused by the saltus of the film layer interface, so its LIDT is greatly increased. This is very important for laser weapons that focus on laser damage threshold.

To sum up, it can be seen that the application of graded-index high reflective film for the laser reflector can improve the beam quality and output power of the laser. If this application can be popularized in the field of laser countermeasure, it will certainly promote the laser weapon to develop
towards the direction of high energy output.

4.2. Graded-index comb notch filter and their typical applications

Notch filter is defined as the filter that removes a certain band from a section of spectrum in the field of optical thin film [24,25], as shown in figure 6.

As the refractive index of the notch filter with gradual refractive index changes periodically, it can be designed according to the rugate-like theory and prepared by subdividing it into a series of thin uniform refractive index film layers. Cutting off multiple certain bands in a section of the spectrum refer to present high reflection in multiple certain bands of the section of the spectrum and present high transmittance in remaining bands of the section of the spectrum. Therefore, the graded-index comb notch filter can also be regarded as an advance of the graded-index high reflective film.

Graded-index comb notch filters are commonly used in laser protection equipment based on linear optics. Laser protective equipment based on linear optics can be divided into three types: the first type is absorption laser protective equipment, which is mainly made of laser protective materials with high transmittance in the visible region and better cutoff depth at the laser wavelength [26]. High enough transmittance of the visible region could improve the observation ability of our observer or equipment. Better cutoff depth could ensure a high attenuation of the laser signal emitted to the enemy and reduce the damage of enemy laser weapons against our observer or equipment [27]. The second type is
reverse laser protective equipment, coating the high reflectivity film (the graded-index high reflective film will be superior to protect lens system in laser wavelengths, high reflectivity could reflect the certain wavelength from enemy laser and ensure our observer or equipment out of the irradiation of enemy laser. The third type is composite laser protective equipment, a kind of protective equipment integrating both of the above two types technologies. It has the comprehensive performance of absorption and reverse protective equipment, and can react on two or more certain wavelengths of laser. This is a typical application of negative filter films with graded refractive index [28]. A typical application of graded-index comb notch filter refers to this. The notch filter for laser protection means that the a certain optical signal which is the cutoff band (as shown in figure 7) is reflected, while useful optical signal which is the pass band (as shown in figure 7) is transmitted.

With the continuous development of laser technology, laser countermeasure have been developed to have polychromatic (multiple wavelength) characteristics. Due to the limitation of natural optical film materials, the traditional notch filter film stack can only achieve the optical signal cut-off of a single band. In order to cover all threatening laser wavelengths with the traditional notch filter, the laser system needs to be equipped with many filters, and the system will be very complex and bulky. It can be said that in the future battlefield, composite laser protective equipment can more effectively protect spectral detectors for imaging or observation and human eyes from laser damage. Due to the continuous change of refractive index, graded-index comb notch filter can replace many materials lacking in traditional optical thin film design. It is not limited by the characteristics of a single film material and it could achieve such a difficult spectral requirement as comb notch filter. In addition, the graded-index thin film has the characteristics of high LIDT, so the comb notch filter film has become an urgent military requirement in the field of laser countermeasure.

5. Conclusion
Existing a lots of studies have shown that the refractive index of the graded-index changes continuously or as gradient way, the structure of it is noninterface type or rugate-like, so it could adjust the distribution of its refractive index along the normal direction of substrate, thus it could meet a very complex spectrum requirement and reduce the effect of the interface alternation and increase the film mechanical stability. The development direction of graded-index thin film is clear enough, but the practice needs further exploration. The graded-index comb notch filter and the graded-index high reflective film have advantages that traditional filter and reflective film do not have, so they have better performance for improving output power of laser and composite laser protective equipment.

In the past decades, with the rapid development of computer technology and automation technology, the design and preparation technology of graded-index thin films have made significant progress, but the preparation difficulty is still very high, even in the military field, the application of graded-index thin films has not been widely promoted. The commercial software for film stack design with better universality and high compatibility with the equipment is still nearly blank in China, and the high-end domestic coating machine about graded-index thin film is still not industrialized, etc., are the important reasons. The author hopes that the publication of this paper could promote the application of graded-index thin films, and attract more related industrial studiers who are interested in the study of graded-index thin films to join the research team, so as to contribute to the further development of the
preparation technology of graded-index thin films. Meanwhile, we also hope it will influence the technical progress of laser attack and defense equipment, and make it be more in line with the international trends of both defensive and offensive and high cost-effectiveness.

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