



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

MADE
MANUFACTURE
ADVANCED
DESIGN
ENGINEERING

A Critical Assessment of Relevant Methods in the Field of Optical Thin Film Manufacturing

James N. Monks

Name	James Norman Monks	ID Number	2126850
Module	Introduction to Industry 4.0	Module Code	ACPA 7004
Lecturer	Mahesh Kannath	Date	27/07/2022
Assignment	Assignment One: Identify a single process, task, role or activity within the authors industry and assess the efficiency and explore possible employment to i4.0 tech.		
Programme	MSc International Innovation Management	Word Count	1639*

**Excluding content table, titles, captions, figures, tables, references*

Contents

1. Introduction	3
2. Aims & Objectives	3
3. Implementation Methodology.....	3
4. The Production of Optical Thin Film Filters.....	3
4.1 Overview of Optical Filters.....	3
4.2 Deposition Methods	4
4.3 Errors and Efficiencies.....	5
4.4 Optical Performance Errors	5
4.5 Move to Industry 4.0.....	6
5. Conclusion.....	7
6. References	8

1. Introduction

Optical manufacturing has played a part throughout all the industrial revolution stages, with its beginning predating the first 18th century industrial revolution way back in ancient Egypt and Mesopotamia (Enoch, 1999). Through the optical manufacturing life cycle, each industrial revolution has played its part in improving productivity (Wills, 2016). Understanding the state-of-the-art critical assessments within any field is key to understanding the errors and efficiencies and exploring methods to improve such systems. A major component of a modern optical system is the optical coating (Macloed, 1999). This report discusses the current efficiencies by examining the errors in terms of a coatings optical response and quantifies that through systematic errors. The improvement of these errors is also discussed by introducing industry 4.0 solution.

2. Aims & Objectives

The aim of this study is to investigate a process within the field of the optical manufacturing industry. The highlighted process set out within this report includes the production of optical filters. This study analyses the impact of the process and considers the migration into the industry 4.0 revolution.

3. Implementation Methodology

A large proportion of the information found in this report has been drawn on from the authors years of extensive study, and academic and industrial experience. In identifying sources for the literature and supporting claims, Google Scholar and ResearchGate were utilised. Regarding both search engines, broad terms were initially used, followed by a narrowing search to explore the available research articles that have been peer-reviewed. Additionally, relevant technical books have been used. The results found in this report have been produced through MATLAB.

4. The Production of Optical Thin Film Filters

This section aims to explore the optical thin film filter technology, its manufacturing methods, the associated errors, and the advantage of industry 4.0 technology integration.

4.1 Overview of Optical Filters

Optical filters are a device that selectively transmits, reflects and absorbs light at different wavelengths. A reflective filter, often referred to 'dichroic filters', utilises interference theorem to cultivate a specifically designed optical spectrum according to the filter requirements (Macleod, 2021). The underlying technology for optical filters has, although significantly improved, remained the same since its early development, and consists of transparent nanoscale thick layers with alternating and contrasting refractive indices. The layer thicknesses are designed to produce destructive and constructive interference for the reflected and transmitted beams depending on the application and filter type (Monks, 2020). The construction of the thin films is referred to as the coating and it is not uncommon for modern filters to have greater than 100 layers.

The sophistication of the optical coating industry is advancing rapidly to meet the ever-increasing demands of the marketplace and technology. With today's optical systems, it is almost impossible to imagine an optical device that would not rely on an optical coating to assure improved functionality and performance (Monks et al., 2020). These coatings can be found in smart phones, cameras, spectroscopy, architectural windows, car, aeroplanes, infrared device, military navigation and missiles, surveillance, unmanned vehicles; there is an unlimited number of applications, and the demand is only set to increase.

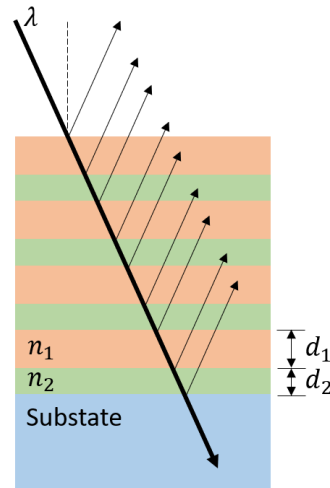


Figure 1. Example of the thin film optical filter construction. Number of layers can vary from 1 to 1000's depending on the filter type, design and optical specification. The film thickness d_x is often on the nanoscale level at $\lambda/4$. The refractive index of the nano films is represented by n_x .

4.2 Deposition Methods

The deposition of optical coatings can be done in a variety of ways (Butt et al., 2022). The most prevalent method, particularly for production level coatings due to the high efficiency compared to alternative methods, occur under vacuum in a process called physical vapour deposition (PVD) (Macleod, 2021). One of the most advanced coating machines available today is the Buhler SyrusPro 1350 (Buhlergroup, n.d). This machine produces high density thin films via two electron beam deposition sources. The electron beam deposition works, *in its simplest form*, by blasting the material target with an electron beam under high vacuum. With precision control, the electron beam results in a high degree of ionisation to transform the target into a gaseous phase which precipitate into a solid film that coats everything within the chamber, including the substrates (Van Dorp and Hagen, 2008).

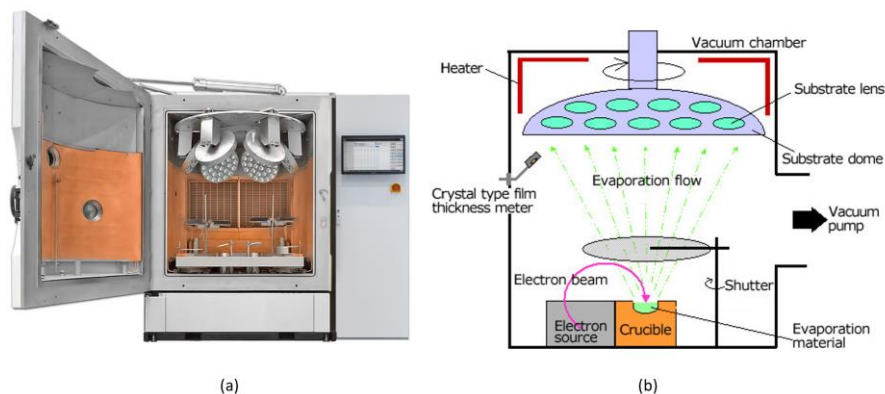


Figure 2. (a) Buhler SyrusPro 1350 (Buhlergroup, n.d). (b) Schematic of a single source electron beam deposition diagram similar to the system found in the Buhler machine (Jeol, n.d).

Despite the refined deposition method, managing the uniformity of layer thickness over the entire substrate and controlling the overall thickness of each individual layer are two of the most significant considerations and challenges. Issues with uniformity result in a characteristic wavelength shift across the surface, whereas thickness control results in a performance decline.

4.3 Errors and Efficiencies

As with any processes, there are random and systematic errors. Random errors are unpredictable, whilst in contrast, systematic errors are predictable and occur due to known sources (Bland and Altman, 1996). With relation to deposition, these errors can be refractive index variations in material or due to atmospheric oxidation, material depletion and replacement, chamber cleanliness, vacuum and atmospheric variation, to name a few. Due to the difficulty in removing random errors, the study found in figure 3 and 5 will focus on systematic errors only.

With a well-trained machine operator, the errors can be below 5%, and with real care and attention, 2% becomes a good error estimate (Macloed, 2021). Figure 3 and 5 shows the thickness errors of 10 run samples for three types of filters and their associated deviation from the filter design with zero errors. The monitoring value of a crystal, single or broadband optical monitoring is known as the turning-point γ_{TP} . The corresponding error φ can be derived in relation to the quarter-wave thickness.

$$Error = \frac{\varphi}{\pi/2} = \frac{\pm\gamma_{TP}}{(\pi/2)\sigma^{1/2}}$$

The optical properties of a device can be derived from the transfer matrix method which is a system used to analyse electromagnetic waves through a stratified medium that goes beyond Fresnel's equations to describe the optical response from multiple interfaces using Maxwell's equations in a one-dimensional form, whilst taking advantage of the continuity conditions across two boundaries (Monks, 2020).

$$\begin{bmatrix} B \\ C \end{bmatrix} = \left\{ \prod_{j=1}^N \begin{bmatrix} \cos k_z L & \frac{i \sin k_z L}{n_j} \\ i n_j \sin k_z L & \cos k_z L \end{bmatrix} \right\} \begin{bmatrix} 1 \\ n_m \end{bmatrix}$$

Where B and C are the normalised electric and magnetic fields at the front interface, respectively. N counts for the number of layers, with each layer of j having a transfer matrix M_j with layer thickness of z .

For simplicity, this report will only focus on the optical transmission for its error and efficiency calculations. However, in real life scenarios a vast number of optical properties would be assessed. The transmission of a thin film system with any number of layers can be derived from the above equation to give the following.

$$T = \frac{4n_0 \operatorname{Re}(n_m)}{(n_0 B + C)(n_0 B + C)^*}$$

4.4 Optical Performance Errors

The efficiency with respect to the current operations, i.e. a well-trained operator and modern coating PVD chambers, is often quantified by the coating's performance error. This will be against a specification supplied by the customer and agreed with the coating engineers prior. However, figure 3 presents an example of three types of optical coatings with figure 3d,e,f demonstrating the deviation from 10 "runs" performed by current operation standards. Runs are defined by number of complete deposition processes.

It is planned to see from figure 3 that efficiency really depends on the type of optical filter. For example, with an error of just 2% standard deviation, the antireflection coating significantly deviates from the ideal response, rendering a large proportion of production out-of-specification. However, the longwave pass filter has a significantly tighter collection between the errors. With respect to the

passband filter, a typical error might be significantly lower than 2% due to type of design but that does not alter the number of *out-of-spec* coatings.

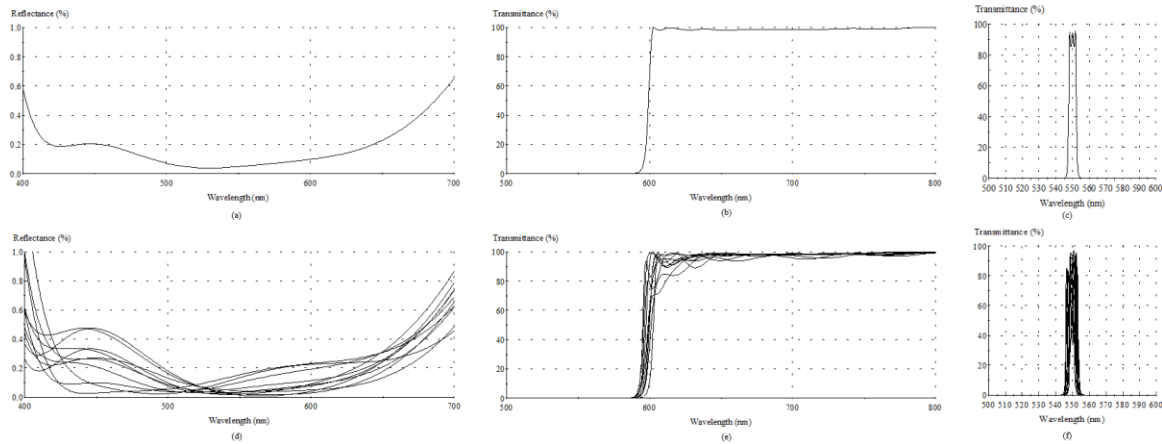


Figure 3. Effect of errors in layer thickness on the optical performance of a range of thin film filters. (a) Four-layer antireflection coating with no errors. (b) Longwave pass filter with no errors. (c) Four-cavity passband filter with no errors. (d) Four-layer antireflection coating with errors of 2% standard deviation. (e) Longwave pass filter with errors of 2% standard deviation. (f) Four-cavity passband filter with errors of 0.5% standard deviation.

The current operating efficiencies mean that a large portion of coated optical element have the potential to miss the specification, particularly for high precision optics where the specifications have extremely tight tolerances.

4.5 Move to Industry 4.0

The manufacturing of optical filters from thin films is noticeably complex (Schallenberg, Ploss, Lappschies and Jakobs, 2010). The requirement of accurate control of the thicknesses for each nanoscale layer is key. As previously discussed, the layer thicknesses are nominal to quarter-wave thicknesses, which requires considerable experience and skill to monitor the deposition process based on conventional quartz crystal monitoring (vd Laan and Frankena, 1977). Nevertheless, with the requirement for higher precision coatings, the monitoring technology also needs to improve. The latest coating chambers are often equipped with single-wavelength optical monitors. Unlike quartz monitoring which is a microelectronic device used to measure the layer thickness, the single-wavelength monitoring works off the turning point method (Zhang, Wang and Lu, 2004). Basically, each layer terminates at a turning point for the monitoring wavelength, as shown in figure 4 for a six-layer coating assembly.

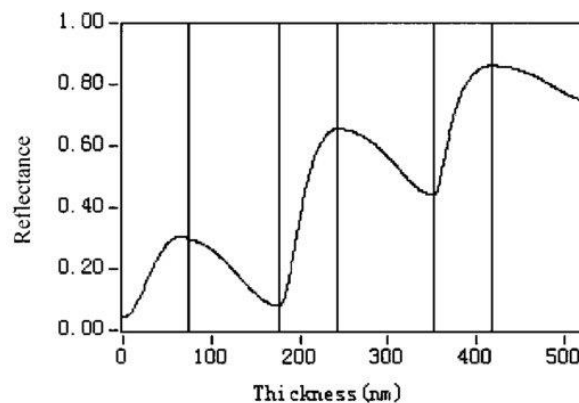


Figure 4. Example of the monitoring curve for the turning point method (Zhang, Wang and Lu, 2004).

Figure 5a,b,c demonstrate the significant improvement with respect to the errors when single-wavelength monitoring is implemented. However, the efficiency and errors are still noticeable and can result in *out-of-spec* products. This is because the single-wavelength monitoring relies on the refractive index knowledge, and if the index is not exact, it can be easy for the monitoring system to go past the turning point, resulting in thicker or thinner than expected layers.

Although single-wavelength monitoring is a welcome improvement, industry 4.0 technology could guide the efficiency and error to near zero as demonstrated in figure 5d,e,f. Unlike single-wavelength, broadband monitoring has the advantage of assessing the refractive index at multiple wavelengths to determine the turning point, leading to a significant improvement in error reduction (Ji et al., 2022). Broadband coupled with machine learning algorithms could take the step beyond standard turning point monitoring (Tran et al., 2022).

A key industry 4.0 technology that is fuelling the growth and uptake include the rapid adoption of artificial intelligence (Gan et al., 2021). Machine learning, a subsection of AI, enables software applications to develop more accurate outcome predictions without being explicitly programmed. The benefit for coating manufacturing is that all the previous decades of data and error analysis could aid reinforcement learning to allow the system to make real-time decision (Kishore et al., 2022) and predict the turning point in advance enabling ultra-precision nanometre accuracy of thin film thicknesses, leading back a zero error standard-deviation where 10 runs would provide a constant and ideal solution found in figure 3a,b,c.

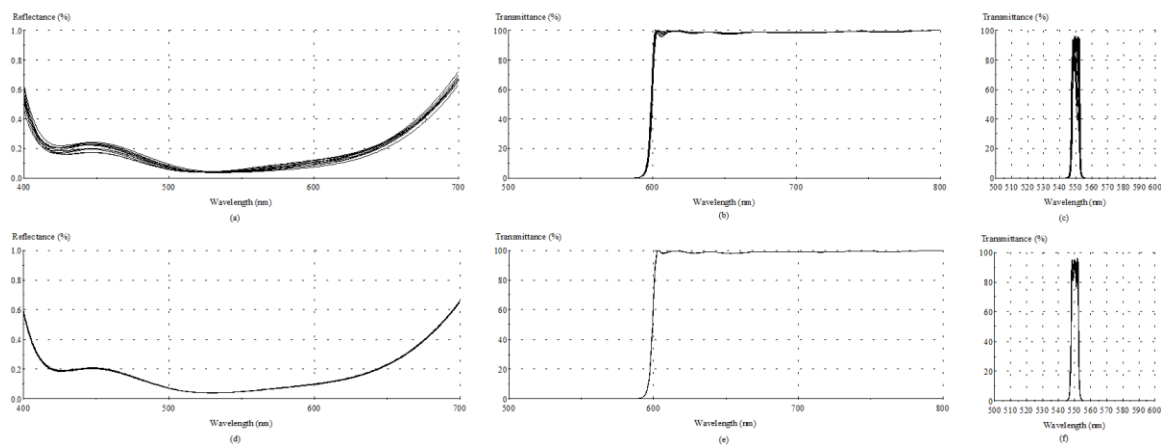


Figure 5. Single wavelength in-situ optical monitoring with errors of 0.3% standard deviation for (a) four-layer antireflection coating, (b) Longwave pass filter, and (c) four-cavity passband filter. Broadband in-situ optical monitoring with errors of 0.05% standard deviation for (a) four-layer antireflection coating, (b) Longwave pass filter, and (c) four-cavity passband filter.

5. Conclusion

The efficiency with respect to the current operation for optical thin film manufacturing process has been assessed in this report with exploration for possible mitigations to current issues being outlined by employing industry 4.0 technologies. Widespread PVDs rely on well-trained operators to monitor and correct systematic errors. The latest technologies including single-wavelength monitoring are helping to improve efficiencies, but they still produce errors that could result in *out-of-spec* products. The introduction of broadband monitoring with machine learning could revolutionise optical filter process through digitising manufacturing. This would pre-empt deviations from the ideal design and adjusting accordingly through real-time decision making without delay or need for an operators input providing a near 100% throughput.

6. References

- Bland, J. and Altman, D., 1996. Statistics Notes: Measurement error. *BMJ*, 313(7059), pp.744-744.
- Buhlergroup, n.d. SyrusPro Vacuum Coating Series | Bühler Leybold Optics. [online] Buhlergroup.com. Available at: <https://www.buhlergroup.com/content/buhlergroup/global/en/products/syruspro_series_precisionopticsvacuumcoater.html> [Accessed 17 July 2022].
- Butt, M., Tyszkiewicz, C., Karasiński, P., Zięba, M., Kaźmierczak, A., Zdończyk, M., Duda, Ł., Guzik, M., Olszewski, J., Martynkien, T., Bachmatiuk, A. and Piramidowicz, R., 2022. Optical Thin Films Fabrication Techniques—Towards a Low-Cost Solution for the Integrated Photonic Platform: A Review of the Current Status. *Materials*, 15(13), p.4591.
- Enoch, J., 1999. Remarkable lenses and eye units in statues from the Egyptian Old Kingdom (ca. 4500 years ago): properties, timeline, questions requiring resolution. *SPIE Proceedings 3749*, 18th Congress of the International Commission for Optics.
- Gan, T., Kanfoud, J., Nedunuri, H., Amini, A. and Feng, G., 2021. Industry 4.0: Why Machine Learning Matters?. *Lecture Notes in Mechanical Engineering*, pp.397-404.
- Jeol, n.d. Electron Beam Source for Electron Beam Deposition | Introduction to JEOL Products | JEOL Ltd.. [online] Jeol.co.jp. Available at: <<https://www.jeol.co.jp/en/science/eb.html>> [Accessed 21 July 2022].
- Ji, X., Zhang, J., Jiao, H., Cheng, X., Wang, Z., Kochikov, I., Sharov, A. and Tikhonravov, A., 2022. Production of ultra-steep dichroic filters with broad band optical monitoring. *Optics Express*, 30(13), p.22501.
- Kishore, S., Vasukidevi, G., Prasad, E., Patnala, T., Reddy, V. and Chanda, P., 2022. A Real- Time Machine learning based cloud computing Architecture for Smart Manufacturing. 2022 International Conference on Applied Artificial Intelligence and Computing (ICAIC).
- Macleod, A., 1999. The early days of optical coatings. *Journal of Optics A: Pure and Applied Optics*, 1(S), pp.779-783.
- Macleod, h., 2021. Thin-film optical filters. 5th ed. [S.l.]: CRC PRESS.
- Monks, J., 2020. Shift-free Wide-angle Metamaterial Narrowband Filters for Anti-laser Striking Applications. Ph.D. Bangor University.
- Monks, J., Williams, J., Hurst, A. and Wang, Z., 2020. Shift-free fixed-line laser protection filter technology. *Technologies for Optical Countermeasures XVII; and High-Power Lasers: Technology and Systems, Platforms, Effects IV*, 1153908.
- Schallenberg, U., Ploss, B., Lappschies, M. and Jakobs, S., 2010. Design and manufacturing of high-performance notch filters. *SPIE Proceedings*.
- Tran, V., Mai, H., Nguyen, H., Duong, D., Vu, V., Hoang, N., Nguyen, M., Mai, T., Tong, H., Nguyen, H., Nguyen, Q. and Nguyen-Tran, T., 2022. Machine-learning reinforcement for optimizing multilayered thin films: applications in designing broadband antireflection coatings. *Applied Optics*, 61(12), p.3328.
- van Dorp, W. and Hagen, C., 2008. A critical literature review of focused electron beam induced deposition. *Journal of Applied Physics*, 104(8), p.081301.
- vd Laan, C. and Frankena, H., 1977. 4.2 Monitoring of optical thin films using a quartz crystal monitor. *Vacuum*, 27(4), pp.391-397.
- Wills, S., 2022. How the Great War Changed the Optics Industry. [online] Optica-opn.org. Available at: <https://www.optica-opn.org/home/articles/volume_27/january_2016/features/how_the_great_war_changed_the_optics_industry/> [Accessed 16 July 2022].
- Zhang, C., Wang, Y. and Lu, W., 2004. Single-wavelength monitoring method for optical thin-film coating. *Optical Engineering*, 43(6), p.1439.