ON-LINE RECOGNITION OF DEVELOPING CONTROL CHART PATTERNS
QUARTER WAVE STACK MODEL SIMULATION FOR OPTICAL EDGE FILTER DESIGN USING OCTAVE

ABUBAKAR MOHAMMED BELLO

A dissertation submitted in fulfilment of the
requirements for the award of the degree of
Master of Science (Physics)

School of Sciences
Faculty of Science
Universiti Teknologi Malaysia

AUGUST 2019

DEDICATION

This thesis is dedicated to my father who taught me that, the best kind of knowledge to have is that which is learned for its own sake. This is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

ACKNOWLEDGEMENT

I thank almighty Allah, the Almighty, the Omnipresent the Omniscient. He who full. His wisdom to every part of the universe. I would like to express my sincere gratitude to my supervisor, Dr. Muhammed Firdaus Omar, for encouragement, guidance, critics and friendship throughout my research and assistance in finalizing this dissertation. I also wish to thanks Dr. Amirrudin Bin Shaari for his advice and motivation. Without their continued support and interest, this thesis would not have been the same as presented here

I am very grateful to Federal Polytechnic Bauchi and Tertiary Education Trust Fund (TETFUND) for funding my study. Also, I appreciate my heartfelt university (Universiti Teknologi Malaysia) at large for providing conducive environment for learning.

Notwithstanding, my sincere gratitude goes to my parent (late Mohammed Bello Bajoga and Hajiya Adda) for their support, inspiration and prayer. Thanks to my wife Adama Aliyu for her sacrifice and enduring. This include a support and prayers from my aunty Hajiya Zainab her husband Malam Sambo, Brothers (Umar Bello,Nura Bello and Mustapha Bello) and sister (Sadiya Bello Aisha Bello and Aisha Bello). Finally, thank to my colleagues and all the members of our families for the prayer, patient and supports on various occasion.

.

ABSTRACT

Optical filter by virtue of their special functions to block a particular wavelength or range of wavelength and transmit the rest of the spectrum have received research attention for the past few decades. Recently, optical filter based on multilayer coating are more focused due to potential to manipulate filter properties by changing layer thickness in order to apply in various fields. Quarter wave stack (QWS) model is one of the approaches to design optical filter such as edge filter. However, to obtain desire minimum specification need an optimization. Therefore, in this study aims to design optical edge filter based QWS model by optical matrix methods in Octave software and fabricate it based on the result obtained using RF magnetron sputtering. Prior to the design, MoS_2 and Si are being choose for high (H) and low (L) refractive index materials respectively. The optimum twenty-four (24) number of layers are determined by calculating maximum transmittance obtained. The Rayleigh wavelength (λ_{ex}) of 405 nm ,532 nm and 633 nm are selected and 'glass|12HL|air' configuration is set for the design simulation. Then, the cut-on wavelength (λ_{cut-on}) and cut-off wavelength ($\lambda_{cut-off}$) of successful designed optical edge filter are measured. The result shows that the cut-on wavelength of 408.11 nm, 536 nm and 640.25 nm with minimum effective transmission (MET) of 32.3%, 31.3% and 32% respectively are obtained. Edge filter for λ_{cut-on} = 633 nm λ_{ex} is selected and fabricated to obtained layer thickness same as generated from the simulation. Afterwards, the fabricated filter is characterized by UV–Vis spectroscopy and field emission scanning electron microscope (FESEM). The result from UV-Vis spectra showed that λ_{cut-on} of fabricated filter at 700 nm with MET of 36%. Moreover, the Filmetric result give the λ_{cut-on} at 640 nm with 30% MET for λ_{ex} = 633 nm which is very close as compare to the simulated result. In conclusion, the result of the present study shows a good correlation between simulation and the Filmetric methods with a bit deviation value of λ_{cut-on} for fabricated filter.

ABSTRAK

Turas optik berdasarkan fungsi istimewanya untuk menghalang panjang gelombang tertentu atau julat panjang gelombang dan memancarkan spektrum selebihnya telah mendapat perhatian penyelidikan sejak beberapa dekad yang lalu. Kebelakangan ini, turas optik berdasarkan salut berbilang lapis lebih difokuskan disebabkan keupayaan untuk memanipulasi sifat turas dengan mengubah ketebalan lapisan untuk digunakan dalam pelbagai bidang. Model susunan gelombang sukuan (QWS) adalah salah satu pendekatan untuk merekabentuk turas optik seperti turas bucu. Walau bagaimanapun, untuk mendapatkan spesifikasi minimum yang dikehendaki memerlukan pengoptimuman. Oleh itu, kajian ini bertujuan untuk merekabentuk turas optik berasaskan model QWS melalui kaedah matrik optik dalam perisian Octave dan membuatnya berdasarkan hasil yang diperoleh menggunakan percikan RF magnetron. Sebelum rekabentuk, MoS2 dan Si dipilih masing-masing untuk bahan indeks biasan tinggi (H) dan rendah (L). Dua puluh empat (24) lapisan optimum ditentukan dengan mengira tranmitans maksimum yang diperolehi. Panjang gelombang Rayleigh (λ_{ex}) iaitu 405 nm, 532 nm dan 633 nm dipilih dan konfigurasi 'kaca|12HL|udara' disetkan untuk simulasi rekabentuk. Kemudian, panjang gelombang *cut-on* (λ_{cut-on}) dan panjang gelombang *cut-off* ($\lambda_{cut-off}$) bagi turas optik bucu yang berjaya direkabentuk diukur. Hasil menunjukkan bahawa λ_{cut-on} 408.11 nm, 536 nm dan 640.25 nm dengan transmitans efectif minimum (MET) adalah masing-masing 32.3%, 31.3% dan 32% diperoleh. Turas bucu untuk λ_{cut-on} = 633 nm dipilih dan dibuat untuk mendapatkan ketebalan lapisan yang sama seperti yang dijana daripada simulasi. Selepas itu, turas yang dibuat dicirikan oleh spektroskopi UV-Vis dan mikroskop medan pancaran imbasan elektron (FESEM). Hasil daripada spektra UV-Vis menunjukkan bahawa λ_{cut-on} bagi turas yang dibuat pada 700 nm dengan 36% MET. Tambahan pula, hasil Filmetric memberikan λ_{cut-on} pada 640 nm dengan 30% MET untuk λ_{ex} = 633 nm yang mana sangat hampir berbanding dengan hasil simulasi. Kesimpulannya, hasil kajian ini menunjukkan hubungkait yang baik antara kaedah simulasi dan Filmetric dengan sedikit sisihan bagi nilai λ_{cut-on} untuk turas yang dibuat

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

MTF	-	Multilayer thin film
H	-	High reflective index
L	-	Low refractive index
N	-	Refractive index
T	-	Thickness
CSD	-	Chemical Solution Deposition
RF	-	Radio Frequency
UV-VIS	-	Ultraviolet visible
NIR	-	Near infrared
FESEM	-	Field emission Scanning electron microscope
LWP	-	Long wave filter
SWP	-	Short wave filter
nm	-	Nano- meter
M	-	Matrix
PVD	-	Physical vapour deposition
CVD	-	Chemical vapour deposition
CWL	-	Central wavelength
FWHM	-	Full- wave half maximum
TM	-	Transverse Magnetic field
TE	-	Transverse Electric field
P	-	Plane polarisation in which electric vector is parallel
S	-	Plane polarisation in which the electric vector is perpendicular
MET	-	Minimum effective transmission
QWS	-	Quarter Wave Stack
T	-	Transmission

LIST OF SYMBOLS

Δ	-	Phase thickness
D	-	Thickness
k	-	Extinction coefficient
λ_o	-	Reference or central wavelength
λ_L	-	Wavelength
θ	-	Angle of incidence
B	-	Normalized magnetic field
C	-	Normalized Electric Field
η_o	-	Admittance
ϕ	-	Angle of propagation or phase shift
ρ	-	Amplitude of the reflectance coefficient
ϒ	-	Admittance of Multilayer C/B
N	-	Real part of refractive index
$\lambda_{cut-off}$	-	Cut-off wavelength
λ_{cut-on}	-	Cut- on wavelength
λ_{ex}	-	Rayleigh wavelength
λ	-	Wavelength
%		Percentage

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Problem Background

In the present era, optical filters have gained a renews interest due to their increasing request for various applications such as analytical instrument, florescence, microscope, Raman spectrometer, clinical chemistry, or machine vision inspection. These devices are accessible in the market such as band pass filter, high pass filter, low pass filter, and band stop filter (Butt et al. 2016; Elyutin, Butt, and Khonina 2017; Piegari and Flory 2013) .

An optical filter can be designed in two different ways, first by using the properties of the deposited materials to absorb light of a given wavelength this is termed as absorption filter (Ng et al. 2019), but this types of filter can be easily damage. The second method of design is using the interference effect of light. This method of design filter is an ideal kind of thin film filter that provides the designer with a wide range of design parameter to produce the require characteristic (Nazar, Ali, and Jasem 2016). The basic types of interference filter consist of a stack of high and low refractive index materials each of one quarter (1/4) wavelength thickness. However, the performance of this types of an optical filter depends on the number of layers, their thickness, and refractive index difference between the layers (Butt et al. 2016; Nazar and Algaffar 2018).

Multilayer thin film (MTF) filter combines attractive properties of several materials. Moreover, MTF filters play a significant role to provide the highest standard such as improvements in transmission, reflection, blocking, and both transmitted and reflected wave front properties. It is comprised of a sequence of boundaries sandwiched between different materials to form a thin film (M. A. Butt, Fomchenkov, and Khonina 2017). Hence, MTF can be used for many applications such as computer disk, optical filter, anti-reflector, solar cells, and in telecommunication industries (Muhammad A. Butt, Fomchenkov, and Khonina 2017).

MTF filter based on Quarter-wave stack (QWS) model is one the most important method in assemble optical filter that consists of multiple alternative layers of high and lower dielectric materials. QWS model is a basic building block for thin-film filters which made up of alternating of high and low index materials. Each one quarter (1/4) of an optical wavelength in thickness, the light of a specific wavelength is very strongly reflected. The other benefit of using quarter wave stack is that it is materials independent and straight forward than other method (Nazar et al. 2016).

Normally, MTF filter based QWS model has been fabricated for many years using different methods such as spray pyrolysis (Maho et al. 2016), radio frequency (RF) magnetron sputtering (Randhawa 1988), thermal evaporation (Maho et al. 2016), and sol-gel (Bronnbauer et al. 2018). Design this optical filter using simulation will give the exact thickness, the number of layers, cut-on and cut-off wavelength and minimum transmission.

In this present work, Octave software is used to simulate a computer program for MTF filter design and fabricate it using RF magnetron sputtering as adopted by (Boyd et al. 2015). The aforementioned software has advantage over other due easy to usage, built-in support of a complex number, and extensibility in form of a user-defined function (Selhofer and Oliver 2019). Furthermore, the simulated program designed using octave software to obtained the optical performance of the filter may be used to solve the MTF filter fabrication problems and also hoping that high performance filter may be obtained.

Molybdenum disulphide (MoS_2) and Silicon (Si) materials are used in optical edge filter for both simulation and fabrication study as adopted (Chromik et al. 2017; Cong et al. 2018). This structural and the optical properties of the fabricated filter can be characterized using field emission scanning electron microscope (FESEM) and ultraviolet visible (UV-Vis) spectroscopy. The result obtained should be similar.

1.2 Problem Statement

In recent years, the MTF edge filter has gained a lot of research interest due to their growing demand in numerous applications. The edge filters have an ultra-steep edge between the absorbing and transmitting spectral region. It has advantage over other types of filter due an excellent blocking of laser line, environmental stable with near infinite life time.

The optical filter can be designed using optical software such as optilayer software (Xie et al. 2017), open filter software (Elyutin et al. 2017), , MATLAB (Abbas, Salman, and Hashim 2017) and fabricated using one of the fabricating method such as RF magnetron sputtering (Benetti et al. 2017), chemical solution deposition (Pejjai et al. 2017), electrodeposition (Maho et al. 2016), solution growth (Eslamian 2017), thermal evaporation and spray pyrolysis method. However, Trubetskov (2013), Kedawat (2014) and Zhupanov (2017) affirmed that the design of optical filter followed by the fabrication of the attained result gives better optical performance and optimum number of layers

In this regard, this study aim is to use optical matrix methods in octave software to design MTF Edge filter based on QWS model and fabricate it via RF magnetron sputtering technique and compare the result with Filmetric web application.

1.3 Objectives of the Research

The objectives of this research are as follows:

(a) To design and optimize a QWS model simulation for MTF optical filter
(b) To fabricate optical edge filter using QWS model simulation result.
(c) To characterize the structural and optical properties of the fabricated edge filter and measure it optical performance.

1.4 Scope of the Research

The MTF edge filter based on QWS model is simulated using octave software. Optimization on the number of layers, the cut-on and cut-off wavelength of the edge filter performance. The simulation result obtained is fabricated using MoS_2/Si series via RF magnetron sputtering. The characterization is identified using UV-Vis spectrometer and FESEM for optical and structural properties respectively. The minimum effective transmission, cut-on and cut-off wavelength of fabricated filter is determined from UV- Vis spectrum analysis. The performance of edge filter is compared with the result obtained from filmetric web application

1.5 Significant of the Research

The finding of this research contributes greatly to the benefit of optical industries to designing MTF edge filters. It also reduces the costs of production and time for fabrication. Since the simulation result give the exact thickness and the cut-on and cut-off wavelength by using the same approach with the same materials, one can easily fabricate multilayer thin film edge filter based on QWS model approach. It is possible to fabricate an optical filter with a minimum number of layers rather than using a larger number of layers with the same output. In this study working under trial and error can be discontinued.

REFERENCES

Abadias, Grégory, Eric Chason, Jozef Keckes, Marco Sebastiani, Gregory B. Thompson, Etienne Barthel, Gary L. Doll, Conal E. Murray, Chris H. Stoessel, and Ludvik Martinu. 2018. "Review Article: Stress in Thin Films and Coatings: Current Status, Challenges, and Prospects." *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films* 36(2):020801.

Abbas, Sabah Ibrahim, Salman Rasool Salman, and Shaymaa Saadoon Hashim. 2017. "Modeling of High Performance Reflection Coatings for Visible Region." *Australian Journal of Basic and Applied Sciences* 11(11):186–93.

Alluxa. 2015. "Optical Filter and Thin Film Coating -Alluxa -Ptics Redefined." Retrieved July 27, 2019 (https://www.alluxa.com/).

Andrews, David L. 2017. "Electromagnetic Radiation." Pp. 427–31 in *Encyclopedia of Spectroscopy and Spectrometry*. Elsevier.

Assafli, Hayder Touran, Ali Hameed, and Wail Yas Nassir. 2016. "Design High Efficient Reflectivity of Distributed Bragg Reflectors Design High Efficient Reflectivity of Distributed Bragg Reflectors." *IRAQI Academic Sceintifc Journal* 15(December):13–18.

Belhadi, A., L. Boudjellal, S. Boumaza, and M. Trari. 2018. "Hydrogen Production over the Hetero-Junction MnO2/SiO2." *International Journal of Hydrogen Energy* 43(6):3418–23.

Benetti, D., R. Nouar, R. Nechache, H. Pepin, A. Sarkissian, F. Rosei, and J. M. MacLeod. 2017. "Combined Magnetron Sputtering and Pulsed Laser Deposition of TiO 2 and BFCO Thin Films." *Scientific Reports* 7(1):2503.

Boyd, A. R., L. Rutledge, L. D. Randolph, and B. J. Meenan. 2015. "Strontium-Substituted Hydroxyapatite Coatings Deposited via a Co-Deposition Sputter Technique." *Materials Science and Engineering C*.

Braeuer, Andreas. 2015. "Absorption Spectroscopy." in *Supercritical Fluid Science and Technology*.

Bronnbauer, Carina, Arne Riecke, Marius Adler, Julian Hornich, Gerhard Schunk, Christoph J. Brabec, and Karen Forberich. 2018. "Printing of Large-Scale, Flexible, Long-Term Stable Dielectric Mirrors with Suppressed Side

Interferences." *Advanced Optical Materials* 6(1):1–9.

Butt, M. A., S. A. Fomchenkov, and S. N. Khonina. 2017. "Multilayer Dielectric Stack Notch Filter for 450-700 Nm Wavelength Spectrum." *CEUR Workshop Proceedings* 1900(1):1–4.

Butt, M. A., S. A. Fomchenkov, A. Ullah, M. Habib, R. Z. Ali, and A. Butt. 2016. "Modelling of Multilayer Dielectric Filters Based on TiO 2 / SiO 2 and TiO 2 / MiF 2 for Fluorescence Microscopy Imaging M.A. Butt et Al." *Computer Optics* 40(5):3–7.

Butt, Muhammad A., Sergey A. Fomchenkov, and Svetlana N. Khonina. 2017. "Multilayer Dielectric Stack Notch Filter for 450-700 Nm Wavelength Spectrum." Pp. 1–4 in *Computer Optics and Nanophotonics*. Vol. 1900. Samara University.

Cai, Zhengyang, Bilu Liu, Xiaolong Zou, and Hui Ming Cheng. 2018. "Chemical Vapor Deposition Growth and Applications of Two-Dimensional Materials and Their Heterostructures." *Chemical Reviews* 118(13):6091–6133.

Chen, Wei Ting, Alexander Yutong Zhu, Jared Sisler, Yao-wei Huang, Kerolos M. A. Yousef, Eric Lee, Chengwei Qiu, and Federico Capasso. 2018. "Broadband Achromatic Metasurface-Refractive Optics." *Nano Letters* 18(12):7801–8.

Chromik, Stefan, Alica Rosová, Edmund Dobročka, Alexander P. Kobzev, Martin Hulman, Michaela Sojkova, Peter Hutár, and Daniel Machajdík. 2017. "MoS2 Thin Films Prepared by Sulfurization." (September):56.

Cong, Ridong, Shuang Qiao, Jihong Liu, Jiansong Mi, Wei Yu, Baolai Liang, Guangsheng Fu, Caofeng Pan, and Shufang Wang. 2018. "Ultrahigh, Ultrafast, and Self-Powered Visible-Near-Infrared Optical Position-Sensitive Detector Based on a CVD-Prepared Vertically Standing Few-Layer MoS 2 /Si Heterojunction." *Advanced Science* 5(2).

Deokate, Ramesh J., Ramchandra S. Kalubarme, Chan-jin Park, and Chandrakant D. Lokhande. 2017. "Simple Synthesis of NiCo2O4 Thin Films Using Spray Pyrolysis for Electrochemical Supercapacitor Application: A Novel Approach." *Electrochimica Acta* 224:378–85.

Elyutin, V. V, M. A. Butt, and S. N. Khonina. 2017. "Cold Mirror Based on High-Low-High Refractive Index Dielectric Materials." Pp. 5–9 in *3nd international conference ' 'information technology and Nanotechnology*.

Erdogan, Turan. 2011. "Optical Filters Construction of Optical Filters."

Eslamian, Morteza. 2017. “Inorganic and Organic Solution-Processed Thin Film Devices.” *Nano-Micro Letters* 9(1):3.

Filmetric. 1995. “Thin Film Thickness Measurement System by Filmetrics.” Retrieved July 27, 2019 (https://www.filmetric.com/).

H. Abdullah, Gaillan, Bushra R. Mhdi, and Nahla A.Aljaber. 2012. “Design Thin Film Narrow Band-Pass Filters For Dense Wavelength Division Multiplexing.” *International Journal of Advances in Applied Sciences* 1(2):pp 65-70.

Ismail, Fairuz Diyana, Muhammad Safwan Aziz, Chat Teeka, Jalil Ali, and Preecha Phromphan Yupapin. 2012. “Filter Design Using Multi-Bragg Reflectors.” *World Journal of Modelling and Simulation* 8(3):205–10.

Jadhav, Jeevan and Somnath Biswas. 2016. “Shape-Controlled Magnetic Nanoplatelets of Ni-Doped ZnO Synthesized via a Chemical Precursor.” *Journal of Alloys and Compounds* 664:71–82.

Kedawat, Garima, Vipin Kumar Jain, and Y. K. Vijay. 2014. “Fabrication of Metal Dielectric Metal Multilayer Thin Film: Color Filter.” Pp. 1024–26 in *AIP Conference Proceedings*. Vol. 1591.

Kedawat, Garima, Subodh Srivastava, Vipin Kumar Jain, Pawan Kumar, Vanjula Kataria, Yogyata Agrawal, Bipin Kumar Gupta, and Yogesh K. Vijay. 2013. “Fabrication of Artificially Stacked Ultrathin ZnS/MgF 2 Multilayer Dielectric Optical Filters.” *ACS Applied Materials & Interfaces* 5(11):4872–77.

Kitui, M., M. M. Mwamburi, F. Gaitho, and C. M. Maghanga. 2015. “Optical Properties of TiO 2 Based Multilayer Thin Films : Application to Optical Filters .” *International Journal of Thin Films Science and Technology* 21(1):17–21.

Lee, Soyoung, Gang Yeol Yoo, Byungwoo Kim, Min Kyu Kim, Changwook Kim, Yeun Park, Hee Chang Yoon, Woong Kim, Byoung Koun Min, and Young Rag Do. 2019. “RGB Colored Cu (In , Ga)(S , Se) 2 Thin-Film Solar Cells with Minimal Efficiency Loss Using Narrow- Bandwidth Stop-Band Nano-Multilayered Filters.”

Macleod, Angus. 2010. *Thin-Film Optical Filters*. Taylos and. USA: CRC Press USA.

Macleod, Angus. 2012. “The Quarterwave Stack : 1 . Early History.”

Macleod, Angus. 2013. “The Quarterwave Stack : 3 . A Building Block.”

Maho, Anthony, Catherine Henrist, Bénédicte Vertruyen, Gilles Spronck, Sylvain Nicolay, Pierre Colson, Laura Manceriu, and Rudi Cloots. 2016. “ Comparison of Indium Tin Oxide and Indium Tungsten Oxide as Transparent Conductive

Substrates for WO 3 -Based Electrochromic Devices .” *Journal of The Electrochemical Society*.

Mayrhofer, P. H., A. Kirnbauer, Ph Ertelthaler, and C. M. Koller. 2018. “High-Entropy Ceramic Thin Films; A Case Study on Transition Metal Diborides.” *Scripta Materialia* 149:93–97.

Nazar, Alaa and Abd Algaffar. 2018. “Optimization Multi- Function of Optical Coating.” 9(3):260–65.

Nazar, Alaa, Abd Algaffar, and Narmeen Ali Jasem. 2018. “SYNTHESIS OF NON-POLARIZED SHORT-WAVE PASS FILTERS FOR THREE REGIONS.” *ARPN Journal of Engineering and Aplied Science* 13(4):2006–9.

Nazar, Alaa, Alyaa Hussein Ali, and Narmeen Ali Jasem. 2016. “New Construction Stacks for Optimization Designs of Edge Filter New Construction Stacks for Optimization Designs of Edge Filter.” vol.8(3).

Nazar, Alaa and Narmeen Ali Jasem. 2017. “Numerical Modelling of Edge Filters for (MWIR).” *International Journal of Science and Research (IJSR)* 6(5, May 2017):3–7.

Ng, Ryan C., Juan C. Garcia, Julia R. Greer, and Katherine T. Fountaine. 2019. “Polarization-Independent, Narrowband, Near-IR Spectral Filters via Guided Mode Resonances in Ultrathin a-Si Nanopillar Arrays.” *ACS Photonics*.

Pejjai, Babu, Vasudeva Reddy Minnam Reddy, Kondaiah Seku, Tulasi Ramakrishna Reddy Kotte, and Chinho Park. 2017. “Chemical Bath Deposition of Mn-Doped ZnS Thin Films Using Greener Complexing Agents: Effect of Mn-Doping on the Optical Properties.” *Optik* 130:608–18.

Piegari, Angela and Francois Flory. 2013. *Optical Thin Films and Coatings: From Materials to Applications*. edited by A. Piegari. United kingdom: Elsevier.

Randhawa, H. 1988. “Cathodic Arc Plasma Deposition Technology.” *Thin Solid Films* 167(1–2):175–86.

Randhawa, Sukanya, María Ujué González, Jan Renger, Stefan Enoch, and Romain Quidant. 2010. “Design and Properties of Dielectric Surface Plasmon Bragg Mirrors.” *Optics Express* 18(14):14496.

Selhofer, Hubert and Marcel Oliver. 2019. *Introduction to GNU Octave*. edited by J. Lachniet. USA: Wytheville Community College.

Shinde, M. S., Smt Swapna Samanta, M. S. Sonawane, P. B. Ahirrao, and R. S. Patil. 2015. “Gas Sensing Properties of Nanostructured ZnS Thin Films.” *J. Nano. Adv.*

Mat. 3, No. 2, 99-106 (2015) © 2012 NSP 99 Journal of Nanotechnology & Advanced Materials An International Journal 106(2):99–106.

Sun, Kai, Christoph A. Riedel, Yudong Wang, Alessandro Urbani, Mirko Simeoni, Sandro Mengali, Maksim Zalkovskij, Brian Bilenberg, C. H. de Groot, and Otto L. Muskens. 2018. “Metasurface Optical Solar Reflectors Using AZO Transparent Conducting Oxides for Radiative Cooling of Spacecraft.” *ACS Photonics* 5(2):495–501.

Trubetskov, Michael K., Tatiana Amotchkina, and Alexander V. Tikhonravov. 2013. “Design of Multilayer Optical Coatings with High Stability to Refractive Index Variations.” P. TD.3 in.

Xie, Xiaozhu, Xiandong Huang, Wei Jiang, Xin Wei, Wei Hu, and Qinglei Ren. 2017. “Crossmark.” *Optics and Laser Technology*.

Yu, Kan, Xiao-yang Zhou, Jia-qi Wang, Jing-jing Xu, and Juan-juan Yin. 2014. “A Non-Polarization Short-Wave-Pass Thin Film Edge Filter.” *Optoelectronics Letters* 10(4):247–49.

Zhao, X. J., L. R. Xiao, Z. W. Zhao, L. Guo, H. Q. Ru, N. Zhang, and D. L. Chen. 2014. “Fabrication and Mechanical Properties of Silicon Carbide–Aluminum Oxynitride Nanocomposites.” *Ceramics International* 40(9):14295–303.

Zhupanov, V., I. Kozlov, V. Fedoseev, P. Konotopov, M. Trubetskov, and A. Tikhonravov. 2017. “Production of Brewster Angle Thin Film Polarizers Using a ZrO_2/SiO_2 Pair of Materials.” *Applied Optics* 56(4):C30.