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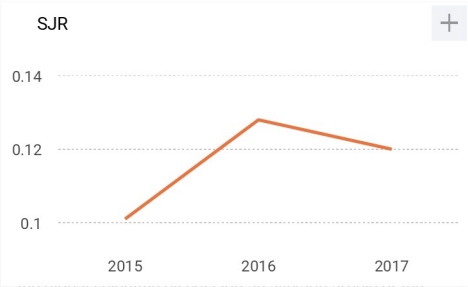

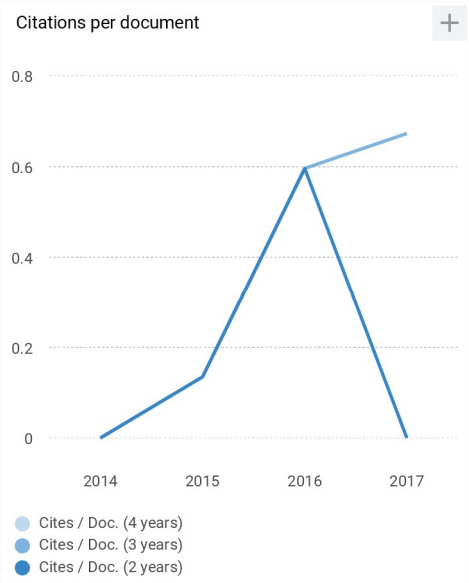

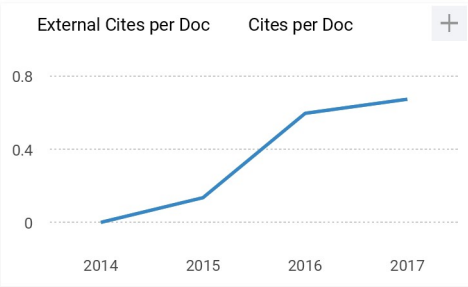

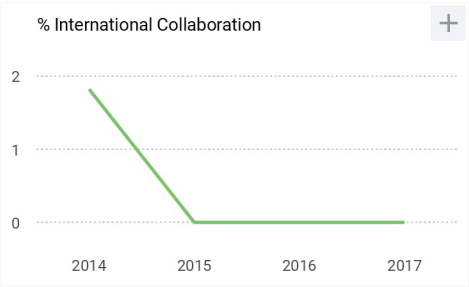

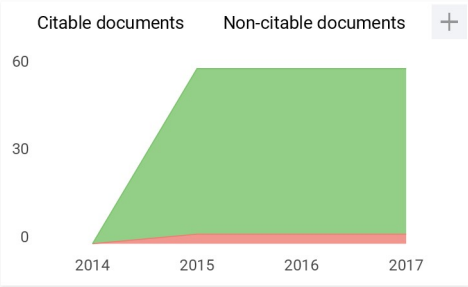

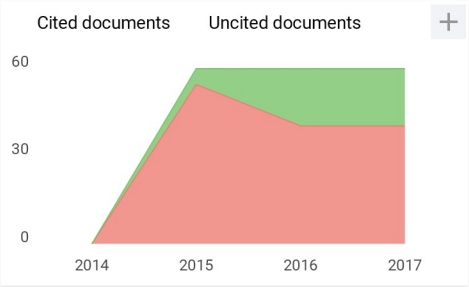

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TABLE OF CONTENTS

1. **Design and Implementation of Taxi Advertisement System** *Yu-Chia Hsu[1], Chih-Sheng Wang[2], Shih-Fan Chou[3], Ai-Chun Pang[4], Pi-Chen Chiu[5], and Shu-Jye Chang[6]* {[1.2.3.4]Computer Science and Information Engineering National Taiwan University Taipei, Taiwan, R.O.C, [5.6]Information and Communications Research Laboratories Industrial Technology Research Institute Hsinchu, Taiwan, R.O.C} ---------- 1
2. **Raspberry Pi Based Laser Spot Detection** *Aryuanto Soetedjo[1], M. Ibrahim Ashari[2], Ali Mahmudi[3], and Yusuf Ismail Nakhoda[4]*{[1.2.3.4]Department of Electrical Engineering National Institute of Technology (ITN) Malang, Indonesia} ---------- 7
3. **The Indonesian Language Speech Synthesizer Based on the Hidden Markov Model** *Kevin Alfianto Jangtjik[1] and Dessi Puji Lestari[2]*{[1.2]Informatics/Computer Sciences Study Program Institut Teknologi Bandung Bandung, Indonesia} ---------- 12
4. **A Prototype of Indonesian Dictation Component for Typing and Formatting Document Using a Word Processor Software** *Devin Hoesen[1] and Dessi Puji Lestari[2]*{[1.2]Department of Informatics Institut Teknologi Bandung Bandung, Indonesia} ---------- 17
5. **New Probabilistic Approach for Identification Event Severity Index Due To Short Circuit Fault** *[1]Nanang [2]Hariyanto BambangAnggoro[3]Randi Noegroho* {[1.2.3]Electrical Power Engineering Institut Teknologi Bandung Bandung, Indonesia} ---------- 22
6. **Effect of Start-Stop Cycles and Hydrogen Temperature on the Performance of Proton Exchange Membrane Fuel Cell (PEMFC)** *F. I. Sempurna[1], Sirliyani[2], Y. P. Handoko[3], I. M. Nurdin[4], and H. Devianto[5]* {[1.2.3.4.5]Dept. Of Chemical Engineering Institut Teknologi Bandung, Jl. Ganesha 10, Bandung 40132, Indonesia} ---------- 27
7. **Implementation of Electronic Medical Record in Community Health Center Towards Medical Big Data Analytics Application** *Agung W. Setiawan[1], Nedya Utami[2], Tati R. Mengko[3], and Adi Indrayanto[4]*{[1.2.3]Biomedical Engineering Research Group School of Electrical Engineering and Informatics Institut Teknologi Bandung Bandung, Indonesia,[4]Electronics Research Group School of Electrical Engineering and Informatics Institut Teknologi Bandung Bandung, Indonesia} ---------- 30
8. **Real-time Implementation of Maximum a Posteriori (MAP) Based Noise Reductions Using Leon 3 System on Chip** *Muhammad H. Santriaji[1], Hilman Mauludin[2], Dian Surgawiwaha[3], and Trio Adiono[4]* {[1.2.3.4]Institut Teknologi Bandung} ---------- 36
9. **Feature-based Noise Robust Speech Recognition on an Indonesian Language Automatic Speech Recognition System** *Cil Hardianto Satriawan[1] and Dessi Puji Lestari[2]* {[1.2]Department of Electrical and Computer Engineering, Institut Teknologi Bandung Jl. Ganeca no. 10, Bandung, Indonesia} ---------- 42
10. **Handwriting Recognition Using River-Lake Skeletonization with Combination of Structural Elements Similarity Classification** *Iping Supriana[1] and Mastur Jaelani[2]* {[1.2]School of Electrical Engineering and Informatics Institut Teknologi Bandung Jalan Ganesa 10 Bandung, Indonesia}-- 47
11. **Development of Assessment Method for Information Technology and Business** *Aceng Salim[1] and Arry Akhmad Arman[2]* {[1.2]Information System and Technology Bandung Institute of Technology Jl. Ganesha No. 10 Bandung, 40132 Indonesia} ---------- 53
12. **Automated Ground Station with Customized Rotator for Antenna Pointing using Compass Sensor** *Rama Setya Anggara[1], Heroe Wijanto[2], Agus D. Prasetyo[3], and Budi Syihabuddin[4]* {[1.2.3]School of Electrical Engineering Telkom University Bandung, Indonesia} ---------- 59
13. **Characteristics of S-bend Optical Waveguides Based on Back-to-Back and Sinusoidal Structures** *Indah Juningtiaz Devayani[1], Ary Syahriar[2], and Dwi Astharini[3]*{[1.2.3]Electrical Engineering Department University of Al Azhar Indonesia Jakarta, Indonesia} ---------- 65
14. **Dispersion Relation of 1-D Photonic Crystal** *Firdaus Akbar[1], Ary Syahriar[2], and Ahmad H. Lubis[3]* {[1.2.3]Electrical Engineering Department Universitas Al Azhar Indonesia Jakarta, Indonesia} -------- 69

15. **Image Based Water Gauge Reading Developed with ANN Kohonen** *Teguh Triantoro[1], F. Rizal Batubara[2], and F. Fahmi[3]* {[1.2.3]Electrical Engineering Department University of Sumatera Utara Medan, Indonesia} ---------- 74
16. **Study on Routing and Congestion Control with Cross layer Scheme in Wireless Ad Hoc Network** *Istikmal[1], Adit Kurniawan[2], and Hendrawan[3]* {[1.2.3]School of Electrical Engineering and Informatics Institut Teknologi Bandung [1]Telkom University Bandung, Indonesia} ---------- 79
17. **Fluid Dynamics and Kinetic Simulation for Steam Reforming of Ethanol Using a Microchannel Reactor** Y. W. Budhi, H. Devianto, F. Mahardhika, L. Ignacia, H. A. Mikhael {[1.2.3.4]Dept. of Chemical Engineering, Institut Teknologi Bandung, Jl. Ganesha 10, Bandung 40132, Indonesia} --- 85
18. **Design of Modified Bow-tie Antennas for Partial Discharge Measurement** *Asep Andi Suryandi[1] and Umar Khayam[1]* {[1.2]School of Electrical Engineering and Informatics, Institut Teknologi Bandung Bandung, Indonesia} ---------- 91
19. **A Real Time AMBA Based Audio Coprocessor for System-on-Chip** *Ahmad Zaky Ramdani[1], Mohammad Rois[2], and Trio Adiono[3]*{[1.2.3]School of Electrical Engineering and Informatics Institut Teknologi Bandung Bandung, Indonesia} ---------- 97
20. **Analysis and Design Subnetting Methods: Hybrid Fixed Length Subnet Masking (HFLSM)** *Afwarman Manaf[1], and Daniel S. Bataona[2]* {[1.2]Sekolah Teknik Elektro dan Informatika, Institut Teknologi Bandung Bandung, Indonesia} ---------- 102
21. **Distributed Intrusion Detection System Using Cooperative Agent Based on Ant Colony *Clustering*** *Muhammad N. Abdurrazaq[1], Riyanto T. Bambang[2], and Budi Rahardjo[3]* {[1.2.3]School of Electrical Engineering and Informatics, ITB} ---------- 109
22. **Data Fusion and Switching Function for MAV Navigation System** *Muhammad Faris[1], Adha Imam Cahyadi[2], and Hanung Adi Nugroho[3]* {[1.2.3]Department of Electrical Engineering and Information Technology, Faculty of Engineering, Universitas Gadjah Mada, Jl. Grafika 2 Yogyakarta 55281, INDONESIA} ---------- 115
23. **Insertion Loss Analysis of Low Voltage Power Line Filter based on EMC Standards** *Ekki Kurniawan[1], Basuki R, Porman P[2], Ig. P Wibawa[3], and Deny Hamdani[4]* {[1.2.3]SEE-Telkom University Bandung, Indonesia, [4]STEI-ITB Bandung, Indonesia} ---------- 121
24. **The Modular Concept Design Development of National Electric Car Case Study at Institute of Technology Bandung** *Y. Martinus. P[1], Andar Bagus S[2]* {[1.2]Product Design Department - Institute of Technology Bandung} ---------- 127
25. **A Study on the Impacts of DC Fast Charging Stations on Power Distribution System** *Yohanes Halim Febriwijaya[1], Agus Purwadi[2], Arwindra Rizqiawan[3], and Nana Heryana[4]* {[1.2.3.4]School of Elecrical Engineering and Informatics, Institute of Technology Bandung Jl. Ganesha 10 Bandung 40132, Indonesia} ---------- 136
26. **Magnetic Simulation Comparation of 30 kW Switched Reluctance Motor with 6/4 and 6/10 Design Configurations for Electric Vehicle** *Umar Sholahuddin[1], Agus Purwadi[2], Nana Heryana[3], Arwindra Rizqiawan[4], and Yanuarsyah Haroen[5]* {[1.2.3.4]School of Electrical Engineering and Informatics Institute of Technology Bandung Jl. Ganesha 10, Bandung, Indonesia} ---------- 141
27. **Development of Wireless Battery Monitoring For Electric Vehicle** *Anif Jamaluddin[1], Fengky Adie Perdana[2], Agus Supriyanto[3], Agus Purwanto[4], Inayati[5], and M. Nizam[6]* {[1.2.3]Physics Education Program, Sebelas Maret University Surakarta, Indonesia,[4.5]Chemical Engineering, Sebelas Maret University Surakarta, Indonesia,[6]Mechanical Engineering, Sebelas Maret University Surakarta, Indonesia} ---------- 147
28. **Analysis of Emotional Condition Based on Electrocardiogram Signals** *Dian Nova Kusuma Hardani[1], Oyas Wahyunggoro[2], Hanung Adi Nugroho[3], and Faisal N[4]* {[1.2.3.4]Department of Electrical and Information Technology Universitas Gadjah Mada Yogyakarta, Indonesia [1]Study Program of Electrical Engineering, Faculty of Engineering Muhammadiyah University of Purwokerto, Purwokerto, Indonesia} ---------- 152
29. **Brushless DC Motor Torque Improvement with Magnetic Material Stator Core** *Muhammad Nizam[1], Hery Tri Waloyo[2], Agus Mujianto[3], Inayati[4], and Agus Purwanto[5]* {[1.2.3]Mechanical Engineering, Post Graduate Program SebelasMaret University Surakarta, Indonesia, [4.5]Chemical Engineering Department SebelasMaret University, Surakarta, Indonesia} ---------- 158

30. **Valuating Indonesian C2C and B2C Quality Using eQual: A Preliminary Research** Nur W. Rahayu[1] and Frendy Anggriawan[2]{[1]Informatics Department Universitas Islam Indonesia Yogyakarta, Indonesia [2]Informatics Department Universitas Islam Indonesia Yogyakarta, Indonesia} ---------- 163
31. **Road Density Prediction Updated Methods of Turning Probabilities and Highway Capacities Manual for Achieving The Best Route** *Jian Budiarto[1], Selo Sulistyo[2], I Wayan Mustika[3], and Ardian Infantono[4]* {[1.2.3]Department of Electrical Engineering and Information Technology, Universitas Gadjah Mada Street of Grafika No. 2, UGM Campus, Yogyakarta Indonesia 55281, Indonesia} ---------- 168
32. **System of Negative Indonesian Website Detection Using TF-IDF and Vector Space Model** *Teguh Bharata Adji[1], Zainil Abidin[2], and Hanung Adi Nugroho[3]* {[1.2.3]Department of Electrical Enginering and Information Technology, Faculty of Engineering Universitas Gadjah Mada Jl. Grafika No. 2 Yogyakarta 55281, Indonesia} ---------- 174
33. **Battery Management System via Bus Network for Multi Battery Electric Vehicle** *Dwi Dharma Artakusuma[1], Hadha Afrisal[2], Adha Imam Cahyadi[3], and Oyas Wahyunggoro[4]* {[1.2.3.4]Department of Electrical Engineering and Information Technology Engineering Faculty, Universitas Gadjah Mada} ---------- 179
34. **Negative Content Filtering Based on Skin Texture, Homomorphic Filter and *Localizations*** *Teguh Bharata Adji[1], Fauziazzuhry Rahadian[2], Hanung Adi Nugroho[3] , and Anugerah Galang Persada[4]* {[1.2.3.4]Department of Electrical Enginering and Information Technology, Faculty of Engineering Universitas Gadjah Mada Jl. Grafika No. 2 Yogyakarta 55281, Indonesia} ---------- 182
35. **Enhancing of Fire Resistance on CFRP Using Sokka-Clay Particle For Lightweight Car Body Panel** *Kuncoro Diharjo[1], Sutrisno[2], Triyono[3], Ridwan Afandi[4], and Dwi Aries Himawanto[5]* {[1.3.5]Mechanical Engineering Department, Faculty of Engineering, University of Sebelas Maret, Surakarta, Indonesia, [2.4]Master Graduate in Mechanical Engineering Department, University of Sebelas Maret, Surakarta, Indonesia} ---------- 188
36. **Improvement of Strength on Joint of GFRP/Al5083 Using Epoxy/Al-Powder Adhesive for Electric Vehicle Car Body** *Kuncoro Diharjo[1,a], Yohanes Firdaus[2,b], Wijang Wisnu Raharjo[3,c], D. Danardono Dwi Prija Tjahjana[4,d]* {[1.2.3.4]Dept. of Mechanical Engineering, Faculty of Engineering, Sebelas Maret University, Surakarta, Indonesia} ---------- 193
37. **A Novel System to Display Position of Explosion, Shot Angle, and Trajectory of The Rocket Firing by Using Markerless Augmented Reality ARoket : Improving safety and quality of exercise anytime, anywhere, and real time** *Ardian Infantono[1] and Andria Kusuma Wahyudi[2]* {[1]Department of Aeronautics Indonesian Air Force Academy Yogyakarta, Indonesia [2]Faculty of Computer Science Klabat University Minahasa, North Sulawesi, Indonesia} ---------- 197
38. **Development of Battery Management System for Cell Monitoring and Protection** *Irsyad Nashirul Haq[1], Edi Leksono[2], Muhammad Iqbal[3], FX Nugroho Soelami[4], Nugraha[5], Deddy Kurniadi[6], and Brian Yuliarto[7]*{[1]Doctorate Student at Department of Engineering Physics, Faculty of Industrial Technology, Institut Teknologi Bandung Jalan Ganesha 10, Bandung 40132, Indonesia,[2.3.4.5.6.7]Department of Engineering Physics, Faculty of Industrial Technology, Institut Teknologi Bandung Jalan Ganesha 10, Bandung 40132, Indonesia} ---------- 203
39. **The performance of LiFePO4 battery with graphite waste as anode Material** *Fitria Rahmawati[1], Nosafarma M. Perkasa[2], Agus Purwanto[3], and Muhammad Nizam[4]* {[1.2]Research Group of Solid State Chemistry & Catalysis, Chemistry Department, Sebelas Maret University, Jl. Ir. Sutami 36 A Kentingan, Surakarta, 57126, Indonesia, [3]Department of chemical engineering, Faculty of Engineering, Sebelas Maret University, Surakarta, Indonesia, [4]Department of Mechanical Engineering, Faculty of Engineering, Sebelas Maret University, Surakarta, Indonesia, [1.2.3.4]Research & Dev. For Indonesia Electric Vehicle Consortium Team, Sebelas Maret University, Surakarta, Indonesia} ---------- 209
40. **Comparation of the Slotless Brushless DC Motor (BLDC) and Slotted BLDC Using 2D *Modeling*** *Agus Mujianto[1], Muh. Nizam[2], and Inayati[3]* {[1]Molina program Sebelas Maret University Indonesia [2]Department of Mechanical Engineering Sebelas Maret University Indonesia [3]Department of Chemical Engineering Sebelas Maret University Indonesia} ---------- 212

41. **Comparisons and performance evaluations of RNA seq alignment tools** *Wei-An Wang, Shih-Yao Dai, Chin-Ting Wu, Tzu-Pin Lu, Mong-Hsun Tsai*, *Liang-Chuan Lai, and Eric Y. Chuang* {Graduate Institute of Biomedical Electronics and Bioinformatics National Taiwan University Taipei, Taiwan, Advanced Research Institute for Information Industry Taipei, Taiwan, Department of Public Health, Graduate Institute of Epidemiology and Preventive Medicine National Taiwan University Taipei, Taiwan, Graduate Institute of Physiology National Taiwan University Taipei, Taiwan, [7]Institute of Biotechnology National Taiwan University Taipei, Taiwan} 215
42. **SOx and NOx Impurities Effect on The Performance of Proton Exchange Membrane Fuel Cell (PEMFC) for Electric Vehicle Application** *M. Eviani[1], H. Devianto[2], I. Nurdin[3], Y.P. Handoko[4], E.-A. Cho[5], S.-P. Yoon[6], J. Han[7], and S.-W. Nam[8]*{[1.2.3.4]Department of Chemical Engineering Institut Teknologi Bandung Bandung 40132, Indonesia,[5.6.7.8]Center for Fuel Cell Research, Korea Institute of Science and Technology Seoul, Rep. of Korea} ---------- 219
43. **The Application Model of Learning Management System Quality in Asynchronous Blended Learning System** *Indah Lestari[1] and Bayu Hendradjaya[2]* {[1.2]Sekolah Teknik Elektro dan Informatika Institut Teknologi Bandung, Bandung, Indonesia} ---------- 223
44. **Implementation of ISO 9126-1 Quality Model for Asset Inventory Information System by Utilizing Object Oriented Metrics** *Yuli Fitrisia[4] and Bayu Hendradjaya[2]* {[1.2]School of Electrical Engineering and Informatics Institute of Technology Bandung Bandung Indonesia} ---------- 229
45. **Effect of Power Imbalance on Multiuser Detection of DS-CDMA Systems** *Adit Kurniawan* {School of Electrical Engineering and Informatics, Institut Teknologi Bandung, Bandung, Indonesia} ---------- 235
46. **Video-based System Development for Automatic Traffic Monitoring** *Okaswara Perkasa[1] and Dwi Widyantoro[2]* {[1.2]School of Electrical Engineering and Informatics, Institut Teknologi Bandung, Bandung, Indonesia} ---------- 240
47. **Automatic Conversion From Speech to RAP Music** *Ming-Ju Wu[1], Chun-Hung Lu[2], and Jyh-Shing Roger Jang[3]* {[1]Department of Computer Science, National TsingHua University Hsinchu, Taiwan, [2]Innovative Digitech-Enabled Applications & Services Institute (IDEAS),Institute for Information Industry, Taipei, Taiwan, [3]Department of Computer Science and Information Engineering, National Taiwan University, Taipei, Taiwan} ---------- 245
48. **Six-Step Commutation with Round Robin State Machine to Alleviate Error in Hall-Effect-Sensor Reading for BLDC Motor Control** *Eka Firmansyah[1], F. Danang Wijaya[2], Rendy Aditya W. P. [3], and Ridwan Wicaksono[4]*{[1,2]Lecturer, Electrical Engineering & Information Technology, Engineering Faculty, Universitas Gadjah Mada, Jl. Grafika No. 2, Bulaksumur, Sleman 55281 INDONESIA (telp: (0274) 562011; fax: (0274) 565223), [3,4]Student, Electrical Engineering & Information Technology, Engineering Faculty, Universitas Gadjah Mada} ---------- 251
49. **Proposed Business Process Technology Commercialization: A Case Study of Electric Car Technology Incubation** *Yuniaristanto[1], D. E. P. Wicaksana[2], W. Sutopo[3], M. Nizam[4]* {[1,2,3] Dept. of Industrial Engineering, Faculty of Engineering, Sebelas Maret University, Indonesia, [4]Dept. of Mechanical Engineering, Faculty of Engineering, Sebelas Maret University, Indonesia, [1,2,3,4]Research and Dev. for Indonesia Electric Vehicle Consortium Team, Sebelas Maret University, Indonesia} ---------- 254
50. **Cogging Torque Reduction with Pole Slot Combination and Notch** *F. Yusivar[1], V. Roy H.S. [2], R. Gunawan[3], and A. Halim[4]* {[1,2,3] [4]RTMC Research Group, Electrical Engineering Department Universitas Indonesia, Indonesia} ---------- 260
51. **Synthesis and analysis of Chitosan-Lithium Battery Cell in Various Charge/Discharge Currents** *Achmad Rochliadi[1], Multazam[2], I Made Arcana[3], and Bunbun Bundjali[4]* {[1,2,3,4]Inorganic and Physical Research Groups, Faculty Mathematics and Natural Sciencess Institut Teknologi Bandung Jalan Ganesha No 10 Bandung 40132, Indonesia} ---------- 264
52. **The Induced Current Density Calculation by Charge Simulation Method for Groundedand Isolated Man Model Exposed Under 500 kV Transmission Line** *Anggoro B., Qodir. A***{**School of Electrical Engineering and Informatics – Bandung Institute of Technology Jl. Ganesha 10 Bandung – Indonesia} ---------- 269

53. **State of Charge Estimation for a Lead-Acid Battery Using Backpropagation Neural Network Method** *F. Husnayain[1], A. R. Utomo[1], PS. Priambodo[1]* {[1]Department of Electrical Engineering, Universitas Indonesia, Depok Indonesia} ---------- 274
54. **Academic Ranks Promotion in Higher Education in Indonesia During 1987-2014** *Yanuarsyah Haroen[1,2], Supriadi Rustad[3]* {[1]Professor at School of Electrical Engineering and Informatics [2]Member of Team of Assessment of Academic Ranks and Credit Points of DGHE Ministry of Education and Culture (since 2006-now) [3]Professor at Semarang State University and Director of Human Resource of DGHE Ministry of Education and Culture} ---------- 279
55. **Proposal of TOGAF ADM Enterprise Continuum for Organization-Specific Solution on e-Government** *Aldo Agusdian, Ian Yosef Matheus Edward, Wervyan Shalannanda, and Susmini Indriani Lestariningati* {Telecommunication Engineering, School of Electrical Engineering and Informatics Institut Teknologi Bandung (ITB) Bandung, Indonesia, Computer Engineering, Faculty of Engineering and Computer Science Universitas komputer Indonesia (UNIKOM) Bandung, Indonesia} ---------- 283
56. **Effects of Welding Time and Welding Current to Weld Nugget and Shear Load on Electrical Resistance Spot Welding of Cold Rolled Sheet for Body Construction** *Ario Sunar Baskoro, M. Rizky Trianda, Jos Istiyanto, Sugeng Supriyadi, Danardono A. Sumarsono, and Gandjar Kiswanto* {Mechanical Engineering Department Faculty of Engineering Universitas Indonesia Depok, Indonesia} ---------- 289
57. **Development of Real-Time Roughness Monitoring During Painting Proses for Cold Rolled Steel for National Electric Vehicle Body Materials** *Sugeng Supriadi[#1], Jos Istiyanto[#2], Gandjar Kiswanto[#3], Ario Sunar Baskoro[#4], Danardono A.S.[#5], Bagaskara Aji[#6]* {[#]Dept. of Mechanical Engineering, Universitas Indonesia Kampus Baru UI Depok, Jakarta, Indonesia} ---------- 294
58. **Full-Bridge Inverter Phase-Shifted PWM (FBPS-PWM) Zero Voltage Switching (ZVS) and High Frequency Transformer as Part of DC-DC Converter 311/100V 300W** *Toni[1], F. Danang Wijaya[2], and Eka Firmansyah[3]* {[1,2,3]Department of Electrical Engineering and Information Technology Faculty of Engineering, Universitas Gadjah Mada} ---------- 298
59. **DC-DC Converter as Power Supply of Battery Charger 100 V 300 W Using 25 kHZ Switching Frequency** *Imam Febriyandi, F. Danang Wijaya, and Eka* Firmansyah {Department of Electrical Engineering and Information Technology Faculty of Engineering, Universitas Gadjah Mada} ------- 302
60. **Technical Feasibility for Technology Commercialization of Battery Lithium Ion** *N. Atikah[1], A. H. Al Ghabid[2], W. Sutopo[3], A. Purwanto[4], and M. Nizam[5]* {[1,2,3]Department of Industrial Engineering, Faculty of Engineering, Sebelas Maret University, Surakarta, Indonesia, [4]Department of Chemical Engineering, Faculty of Engineering, Sebelas Maret University, Surakarta, Indonesia, [5]Department of Mechanical Engineering, Faculty of Engineering, Sebelas Maret University, Surakarta, Indonesia, [1,2,3,4,5]Research & Dev. for Indonesia Electric Vehicle Consortium Team, Sebelas Maret University, Surakarta, Indonesia} ---------- 308
61. **Preliminary Study of a Deep Drawing Process Modelling for AL-5083 Aluminium *Material*** *Yatna Yuwana Martawirya[1], Sri Raharno[2], and Daniel Sadono[3]* {[1,2,3]Faculty of Mechanical and Aerospace Engineering Institut Teknologi Bandung, Bandung, Indonesia} ---------- 315
62. **Experimental Design boost ratio converter with hybrid transformer for hybrid power source charging station** *D. A. Asfani[1], Daniar Fahmi[2], Edi Wibowo[3], Heri Suryoatmojo[4], D.C Riawan[5], and Prabowo[6]* {[1,2,3]Electrical Engineering Department Institut Teknologi Sepuluh Nopember Surabaya, Indonesia, [4,5,6]Mechanical Engineering Department Institut Teknologi Sepuluh Nopember Surabaya, Indonesia} ---------- 321
63. **Design of Battery Connection using Copper Conductor with Tin and Silver Coating** *Umar Khayam[1], Budi Sutrisno[2], Agus Risdiyanto[3], Suwarno[4]* {[1,2,3,4]School of Electrical Engineering and Informatics, Institut Teknologi Bandung, Jalan Ganesha 10 Bandung, Indonesia} ---------- 326
64. **Harmonics Mitigation for Offshore Platform Using Active Filter and Line Reactor Methods** *F. Husnayain[1], N. D. Purnomo[2], R. Anwar[2], and I. Garniwa[1]* {[1]Department of Electrical Engineering, Universitas Indonesia, Depok Indonesia, [2]Electrical Engineering Division, PT Pertamina PHE ONWJ, Jakarta, Indonesia} ---------- 331

65. **Partial Discharge Induced Electromagnetic Wave Propagation Characteristics in 70 kV Gas Insulated Switchgear** *Zahrina Hafizhah[1] and Umar Khayam[2]* {[1,2]School of Electrical Engineering and Informatics InstitutTeknologi Bandung Bandung, Indonesia} ---------- 337
66. **Design of Traction Motor 180kW type SCIM for KRL (EMU) Jabodetabek Re-Powering Project** *Andri Setiyoso[1], Hilwadi Hindersyah[2], Agus Purwadi[2], and Arwindra Rizqiawan[2]* {[1]PT. PINDAD (Persero), [2]School of Electrical Engineering and Informatics, Institut Teknologi Bandung, Indonesia} ---------- 341
67. **Analysis of Lead Acid Battery Operation Based on Peukert Formula** *A. R. Utomo, F. Husnayain, and P. S. Primbodo* {Department of Electrical Engineering, Universitas Indonesia, Depok Indonesia} ---------- 345
68. **Design of Circle Shaped Loop Antenna as Partial Discharge Sensor** *Fakhru Rozi and Umar Khayam* {School of Electrical Engineering and Informatics Institut Teknologi Bandung Bandung, Indonesia} ---------- 349
69. **Simulation And Experimental Studies On Braking Response Of Inertial Load Using Magnetorheological Brake** *Ubaidillah[1], A.N.R.S. Permata[2], Triyono[3], D.D.D.P. Tjahjana[4], M. Nizam[5], S.A. Mazlan[6], and F. Imaduddin[7]* {[1,2,3,4]Chassis and Drivetrain Research Group, National Electric Vehicle Consortium Universitas Sebelas Maret, Indonesia, [5,6]i-Kohza Vehicle System Engineering Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia} 353
70. **Implementation of Field Oriented Control for Permanent Magnet Synchronous Motor** *F. Yusivar[1], N. Hidayat[2], R. Gunawan[3], and A. Halim[4]* {[1,2,3,4]RTMC Research Group, Electrical Engineering Department Universitas Indonesia, Indonesia} ---------- 359
71. **An Easy Speed Measurement for Incremental Rotary Encoder Using Multi Stage Moving Average Method** *Arinata Fatchun Ilmiawan[1], Dito Wijanarko[2], Ahmad Husnan Arofat[3], Hilwadi Hindersyah[4], and Agus Purwadi[5]* {[1,2,3]Center of Technology and Innovation, PT LEN Industri Bandung, Indonesia, [4,5]School of Electrical Engineering and Informatics Institute of Technology Bandung} ---------- 363
72. **Partial Discharges in High Voltage Insulations Mechanism, Patterns and Diagnosis** *Suwarno* {School of Electrical Engineering and Informatics Institut Teknologi Bandung, Bandung Indonesia} ---------- 369
73. **A Cost Estimation Model to Assess the Feasibility of Li-Ion Battery Development based on Targeted Cost by Market Approach** *W. Sutopo[1], N. Atikah[2], A. Purwanto[3], D. Danardono D.P.T. [4], and M. Nizam[5]* {[1,2]*Department of Industrial Engineering, Faculty of Engineering, Sebelas Maret University, Surakarta, Indonesia,* [3]*Department of Chemical Engineering, Sebelas Maret University, Surakarta, Indonesia,* [4,5]*Department of Mechanical Engineering, Sebelas Maret University, Surakarta, Indonesia,* [1,2,3,4,5]*Research & Dev. for Indonesia Electric Vehicle Consortium Team, Sebelas Maret University, Surakarta, Indonesia}* ---------- 376
74. **Characterization of 2-stage RF Power Amplifier for FMCW Radar Application** *Achmad Munir [1] and Yudi Yulius Maulana[2]* {[1]Radio Telecommunication and Microwave Laboratory School of Electrical Engineering and Informatics, ITB Bandung, Indonesia, [2]Research Center for Electronics and Telecommunication Indonesian Institute of Sciences Bandung, Indonesia} ---------- 381
75. **Performance Enhancement of Coupled Microstrip Lines Using Split Ring Resonators** *Achmad Munir[1] and Lorenz Rullyna Ginting Soeka[2]* {[1,2]Radio Telecommunication and Microwave Laboratory School of Electrical Engineering and Informatics, ITB Bandung, Indonesia} ---------- 385

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Dispersion Relation of 1-D Photonic Crystal

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***Abstract*— Photonic crystal is a periodic dielectric material that affect the propagation of light. That produces a photonic bandgap. Photonic bandgap is a structure where a range of frequency cannot propagate through the structure. The charateristics can bee seen from the dispersion relation of the light propagate in the structure. In this paper, we use two different methods to simulate the dispersion relation; firstly we use a Plane wave method and secondly we use a transter matrix method. Both methods use a different approach to describe the periodic dielectric structures. In the simulation we try to compare both results and show them in graph of wavevector k vs frequency, with unit cell consisting GaAS as material of the dielectric and air as the gap. The width of GaAS is 0.8 micron and width of the air gap is 0.2 micron. We also rescaling both normalized frequency to be the similar. In the process we examine the normalised frequency values using both methods as well as the difference results appears on the calculations.**

Keywords*— *photonic crystal, plane wave method, transfer matrix method, GaAs, bandgap

I. INTRODUCTION

The electromagnetic waves that propagate through a medium other than vacuum will have their characteristics changed. Frequency, amplitude, wavelength, dispersion, will all changed depends on the medium where it propagate. Photonic crystal is the same, a periodic dielectric structure that affect the propagation of light so that on a range of specific frequency the light wont propagate through the medium.

The periodic dielectric function on photonic crystal have a same structure as crystalline atomic lattice that used in a semiconductors. On solid-state physics the crystal lattice affects the electrons that propagate through it, while at the photonic crystal it affects foton. These two same condition allow us to obtain the characteristics for dispersion relation of photonic crystal as same as on solid-state physics.

We will get the bandgap result in form of band diagram, that will represent the photonic bandgap on wavevector k vs normalized frequency graph. We use normalized frequency so that the solution wont depends on specific frequency range but will work on every frequency range.

In this paper we will only use two different simulation methods, plane wave method and transfer matrix method. Then comparing two different methods to simulate the dispersion relation. We obtain that the simulation results have a slight difference. For the comparison, we refer the transfer matrix method into plane wave method, which have more accurate results. Both of these methods use different approach to calculate the dielectric function for finding dispersion relation, thus resulting on different simulation results.

II. THEORY

A. Maxwell Equation in Dielectric Medium

On photonic crystal, the light wave propagates through a dielectric medium. The wave equation can be solved using macroscopic maxwell equation. Because the wave propagates through a periodicity that have a vector position, the structure does not vary with time and no free charges or currents. In this medium, we also assume that light propagates but there are no sources of light. So, in the maxwell equation we add additional parameter $\rho = 0$ and $J = 0$ and subtitute it into the equation.

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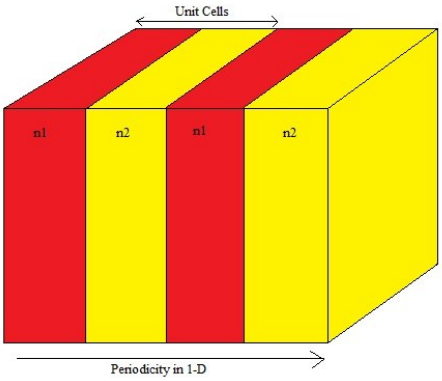

Fig. 1. The structure of one dimension photonic crystal

We then apply a harmonic modes to reduce the time dependant on calculation[1].

$$H(r,t) = H(r)e^{-i\omega t} \tag{1}$$

$$E(r,t) = E(r)e^{-i\omega t} \tag{2}$$

Subtitute the above equation into maxwell and we can obtain the master equation.

$$\nabla \times \left(\frac{1}{\varepsilon_{(r)}} \nabla \times H(r) \right) = \frac{\omega^2}{c^2} H(r) \tag{3}$$

B. Bloch Theorem

On solid-state physics, Bloch theorem was used to obtain the solution on semiconductor atomic crystal lattice. Bloch theorem says that the eigen-function inside an infinite periodic medium can be represented in the form of a plane wave multiplied by a periodic function with periodicity of the lattice[2].

$$H(r) = h(r)e^{ikr} \tag{4}$$

We can also obtain the solution for (3) using Bloch wave. Thus, the master equation became,

$$\frac{\partial^2}{\partial r^2} \frac{1}{\varepsilon(r)} h(r)e^{ikr} = \frac{\omega^2}{c^2} h(r)e^{ikr} \tag{5}$$

C. Plane Wave Method

To obtain the dispersion relation, plane wave method is using the fourier expansion to transfrom and calculate the dielectric function. The dielectric function is expressed with,

$$h(r) = h(r + R_i) \tag{5}$$

With R_i form the crystal lattice vector $R_i = l_1 a_1 + l_2 a_2 + l_3 a_3$. And l_1, l_2, l_3 were integers, a_1, a_2, a_3 were primitive lattice vector. Thus, the periodic dielectric primitive lattice vector on dielectric function is transformed into reciprocal lattice vector using the fourier transform.

$$\varepsilon(r) = \sum_G g(G) e^{iGr} \tag{6}$$

$$H(r) = \sum_G h_{k,n}(G) e^{i(k+G)r} \tag{7}$$

G is reciprocal lattice vector $G = h_1 b_1 + h_2 b_2 + h_3 b_3$ where h_1, h_2, h_3 were integers, b_1, b_2, b_3 were primitive lattice vector. We subtitute (8) and (7) to (5). Then obtain,

$$\sum_{G^\phi} g^{-1}\left(G - G^\phi\right)\left(\left(k + G^\phi\right)(k+G)\right) h_{k,n}\left(G^\phi\right) = \frac{\omega^2}{c^2} h_{k,n}(G) \tag{8}$$

Further, we simplify (9) and transform it into matrix form. Hence,

$$\begin{bmatrix} m_{11} & m_{12} & \cdots & \cdots \\ m_{21} & m_{22} & \cdots & \cdots \\ \vdots & & \ddots & \vdots \\ m_{2N,1} & m_{2N,2} & \cdots & \cdots \end{bmatrix} \begin{bmatrix} h_1(G_1) \\ \vdots \\ h_N(G_N) \\ h_1(G_1) \\ \vdots \\ h_N(G_N) \end{bmatrix} = \frac{\omega^2}{c^2} \begin{bmatrix} h_N(G_N) \\ h_2(G_1) \\ \vdots \\ h_N(G_N) \end{bmatrix} \tag{9}$$

We use (10) to find the dispersion relation with plane wave method. To transform above equation into code there is a general step, which is[3]:

- Given a K point to solve the associating frequency
- Find the reciprocal lattice and choose the G vector set
- Find each of the fourier transform coefficient $\varepsilon^{-1}\left(G - G'\right)$
- Find the $k + G$ and the two unit vector sets
- Calculate the eigen value

D. Transfer Matrix Method

Transfer matrix is another method used to analyze the propagation of electromagnetic waves through a periodic medium. According to Maxwell, light that propagate in layered or periodic dielectric medium have different characteristics on each layer. With transfer matrix method, the field at the end of the layer can be derived from a simple matrix operation.

The layered dielectric medium can be seen as a matrix system that obtained from the sum of individual layer matrices. From the sum results we can obtain the reflectance and transmittance coefficient for the layered dielectric medium and transform it into dispersion relation. The method is then applied to electromagnetic waves with a specific frequency propagating through the layer at normal incidence angle.

To understand the transfer matrix method, we begin with the S-Matrix formalism,

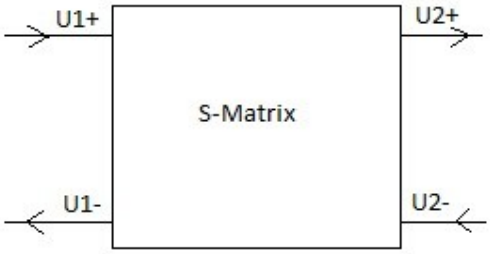

Fig. 2. S-matrix formalism for dielectric layer

From the picture above, we know that in the layered structure there is two different electromagnetic field that occured. The propagating/forward field and the reflected/backward field. The reflected field was a result from reflectance of the propagating field in the boundary between dielectric layer with different refractive index.

Thus, according to S-Matrix formalism, the field characteristics on the dielectric layer is,

$$U_2^+ = t_{12}U_1^+ + r_{21}U_2^+ \tag{10}$$

$$U_1^- = r_{12}U_1^+ + t_{21}U_2^+ \tag{11}$$

Where t_{12} and t_{21} is a transmittance field, while r_{12} and r_{21} is a reflectance field. The matrix form of the equation is,

$$\begin{bmatrix} U_2^+ \\ U_1^- \end{bmatrix} = \begin{bmatrix} t_{12} & r_{21} \\ r_{12} & t_{21} \end{bmatrix} \begin{bmatrix} U_2^+ \\ U_1^- \end{bmatrix} \tag{12}$$

We can further define the S-Matrix and its M-Matrix part using the transform relation between them. If there is no loss and the transmission coefficient t and reflection coefficient r in forward and backward are identical, we get

$$S = \begin{bmatrix} t & r \\ r & t \end{bmatrix} \tag{13}$$

$$M = \begin{bmatrix} 1/t^* & r/t \\ r^*/t^* & 1/t \end{bmatrix} \tag{14}$$

Where: $t/r = -(t/r)^*$, $|t|^2 + |r|^2 = 1$

We use the same S-Matrix above to reconstruct the dielectric function of photonic crystal into matrix form. To obtain these matrices, we use Bloch theorem to explain how the electromagnetic field in each layer was different.

According to Bloch theorem, the electromagnetic field in each layer is a function plane wave times the periodicity. So we get the matrix,

$$\begin{bmatrix} U_{m+1}^+ \\ U_{m+1}^- \end{bmatrix} = M_0 \begin{bmatrix} U_m^+ \\ U_m^- \end{bmatrix} = e^{-ikr} \begin{bmatrix} U_m^+ \\ U_m^- \end{bmatrix} \tag{15}$$

Equation (17) can be reduced to,

$$\left| M_0 - e^{-ikr} \cdot I \right| = 0 \tag{16}$$

Where I is the identity matrix and M_0 is the matrix M. As stated before, the end product of transfer matrix is the dispersion relation. We then find the determinant from (18) to obtain the propagation characteristics. We obtain half of the dispersion relation,

$$e^{-ikr} = \left(\frac{1}{t^*} + \frac{1}{t}\right) \pm \sqrt{\left(\frac{1}{t^*} + \frac{1}{t}\right)^2 - 4\frac{1 - r^* r}{t^* t}} \tag{17}$$

$$cos(kr) = Re\left\{1/t\right\} \tag{18}$$

We need to find the value of $1/t$ to complete the dispersion relation. In the figure below, the light first propagate through medium 1, then traveling across the boundary between medium 1 and 2, then propagate in medium 2, and back from medium 2 to medium 1 again.

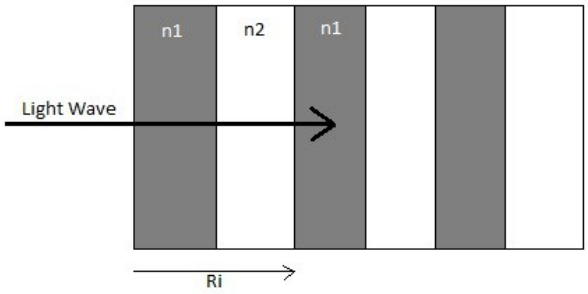

Fig. 3. Light propagation through layered structure

Light that propagate through the medium will change depends on the periodicity. So in matrix form, the dispersion relation for the structure obtained with multiplying all of the propagation matrices. That is,

$$M = M_{21}M_2M_{12}M_1 \tag{19}$$

$$M_{12} = \frac{1}{2n_2}\begin{bmatrix} n_{2+}n_1 & n_{2-}n_1 \\ n_{2-}n_1 & n_2 + n_1 \end{bmatrix} \tag{20}$$

$$M_{21} = \frac{1}{2n_1}\begin{bmatrix} n_{1+}n_2 & n_{1-}n_2 \\ n_{1-}n_2 & n_1 + n_2 \end{bmatrix} \tag{21}$$

Where M_1 is the propagation matrix for medium 1, M_2 is the propagation matrix for medium 2, and M_{12}, M_{21} is the propagation matrix between two layer.

Using (21)(22)(23), we get the value of $1/t$. We then subtitute it with wavevector k and the periodicity d for both dielectric medium. Then our complete dispersion relation using transfer matrix method is,

$$cos(k.r) = cos(k_1d_1 + k_2d_2) - \frac{(k_1 - k_2)^2}{2k_1k_2} sin(k_1d_1) sin(k_1d_2) \tag{22}$$

This equation is the equation of dispersion relation that obtained from multiplication of the matrices in the structure using transfer matrix method. Here the wavevector is,

$$k_n = \frac{\omega}{c_n} \tag{23}$$

And n is the medium number. We subtitute the value of k_1 and k_2 in (22) with (23), so we get the relations between k and ω,

$$\cos(k.d) = \cos\left(\frac{\omega d_1}{c_1} + \frac{\omega d_2}{c_2}\right) - \frac{(\omega/c_1 - \omega/c_2)^2}{2(\omega/c_1)(\omega/c_2)} \sin\left(\frac{\omega d_1}{c_1}\right) \sin\left(\frac{\omega d_2}{c_2}\right) \tag{24}$$

Equation (24) can further be simplified using a normalized frequency to eliminate the differences in value of light speed in the medium 1 and 2,

$$\omega_{norm} = \frac{\omega}{c_{(1,2)}} = \frac{\omega n_{(1,2)}}{c_0} \tag{25}$$

Where $n_{(1,2)}$ is the refractive index of medium 1 and 2, respectively. Subtitute the value of $\omega/c_{(1,2)}$ in equation (24) with (25). Hence, after simplification it become,

$$\cos(k.d) = \cos\left(\frac{\omega}{c_0}(n_1 d_1 + n_2 d_2)\right) - \frac{(n_1 - n_2)^2}{2n_1 n_2} \sin\left(\frac{\omega n_1}{c_1} d_1\right) \sin\left(\frac{\omega n_2}{c_2} d_2\right) \tag{26}$$

Equation (26) is the final equation of dispersion relation with transfer matrix method.

III. Simulation Result and Discussion

A. Dispersion Relation in Uniform and Nonuniform Medium

For the simulation, the material used is GaAs with refractive index = 3.39866 and air gap. The width of the unit cell is 1 micron. Width of the GaAs = 0.8 micron, air gap = 0.2 micron.

We show that the bandgap occured when the structure is nonuniform and compare it with uniform structure. In figure (2) we use transfer matrix method to calculate results. The red lines are dispersion relation when the structure is uniform, and the blue lines are dispersion relation when the structure is nonuniform.

The size of the bandgap increased when the difference between refractive index value of n1 and n2 is increased.

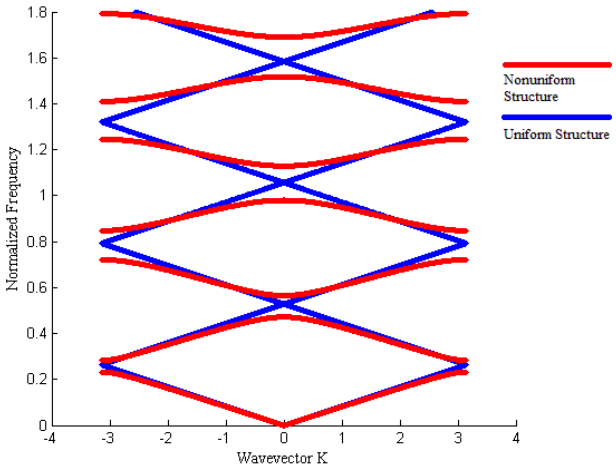

Fig. 4. Dispersion relation for uniform and nonuniform medium

B. Comparison of Dispersion Relation with Plane Wave Method and Transfer Matrix Method

With same simulation parameters, we then compute the dispersion relation using plane wave method and the transfer matrix method. To compare the above results, we need to equalize the value of normalized frequency.

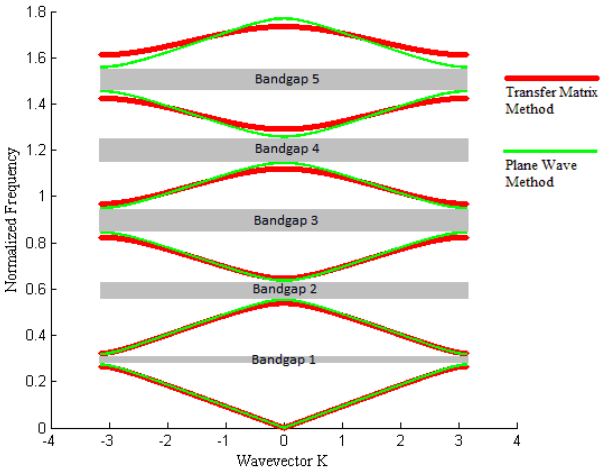

Fig. 5. Dispersion relation with plane wave method and transfer matrix method

From fig. 5, we obtain the value of normalized frequency that occured in all photonic bandgap. We calculate every value of beginning normalized frequency in bandgap 1 to 5. The result then displayed below.

TABLE I. Beginning Normalized Frequency for Each Bandgap

Bandgap Number	*Beginning Normalized Frequency*	
	Transfer Matrix Method	**Plane Wave Method**
1	0.2654	0.2726

Bandgap Number	*Beginning Normalized Frequency*	
	Transfer Matrix Method	**Plane Wave Method**
2	0.5391	0.5527
3	0.8243	0.8438
4	1.12	1.145
5	1.424	1.454

The error result between the two methods is increased as the number of bandgap increased. The number of bandgap means that in the normalised frequency, the bandgap that occur above normalized value 1 will have an increasing error. If we further compute the solution above normalized frequency 2, the error value will be huge. This is because the methods just compute the solution in normalised frequency. Thus, the bandgap solution is credible only between 0 to 1 normalized frequency. In this range, the result between two methods is almost the same, with just 0.0072 in length of error differences.

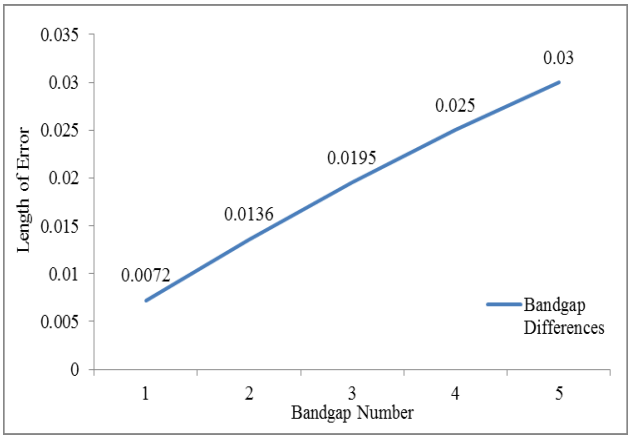

Fig. 6. The error results in two different methods

IV. Conclusion

From the simulation results and discussion, it can be concluded that the plane wave and transfer matrix method can be used to compute the dispersion relation in photonic crystal. Simulating the dispersion relation will show the photonic bandgap that occur when the dielectric structure is nonuniform and periodic. It is different according to the periodicity of the structure. For the uniform dielectric structure, we can see that there is no photonic bandgap phenomena, all frequencies of light will propagate through the structure. In the comparison between two methods, the error of normalized frequency that occured in the beginning of photonic bandgaps increased when the photonic bandgap range is higher. The value of error increased because in the bandgap computation we only compute the normalised frequency, which have credible value only in range 0 to 1. The bandgap that occur above the credible value will have increased into huge number of length of error.

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