TUNGSTEN TRIOXIDE INTEGRATED ALL-FIBER PHASE SHIFTER

By

NORHANIE BINTI BAHTIAR AFFENDY

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

October 2021

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

TUNGSTEN TRIOXIDE INTEGRATED ALL-FIBER PHASE SHIFTER

By

NORHANIE BINTI BAHTIAR AFFENDY

October 2021

Chairman : Muhammad Hafiz bin Abu Bakar, PhD
Faculty : Engineering

All-fiber phase shifter is said to be one of the important components in optical communication and signal processing systems. Additionally, all-fiber phase shifter offers usage in electro-optic systems, fiber lasers, and sensors. The all fiber configuration is attractive due to advantages such as coupling simplicity and low insertion loss. Other than that, they also have a compact packaging and remote usage capability. Weak nonlinearity in conventional fiber imposes the use of extended length of fiber in order to trigger phase shifting. Another way to induce phase shifting includes introducing disruption into the fiber via mechanical deformation as well as acousto-optic effect. There is also effort in developing phase shifters using nonlinear optical phase modulation through cross-phase modulation and stimulated Brillouin scattering. Recently, researchers found another method of utilizing the thermal effect of nanomaterial attached to the microfiber. Previous works had introduced the usage of nanomaterials such as black phosphorus, graphene, and Au nanorods with all exhibiting promising performance. This work was focused on the development of optical fiber taper phase shifter deposited with tungsten trioxide (WO_3), a nanomaterial that has recently been explored for various optical applications. The taper profile used across the experiment are; up and down taper of 5 mm, waist length of 10 mm and waist diameter of 12 µm. Tungsten trioxide (WO_3) was synthesized via the mixing of WO_3 solution with polydimethylsiloxane (PDMS). The concentration of WO_3 was fixed using 5mg/mL for all the variation of spin coating time from 30 s to 150 s with the interval of 30 s and was then tested. The success of the nanomaterial deposition process was validated using UV Vis spectrometer, Field Emission Scanning Electron Microscope (FESEM), Energy Dispersive X-ray Analysis (EDX), Atomic Force Microscope (AFM) and RAMAN Spectroscopy. For phase shifter characterization, pump power was varied from 0 to 220 mW with the interval of 20 mW. The thickness of coating was found to be a factor in the ability of WO_3 to induce phase shifting effect. A blueshift with maximum phase shift of 2.52π and spectral shift efficiency of 0.011 π/mW were obtained for tungsten trioxide integrated all-fiber phase shifter with 120 s spin coating time. Phase shifter with the optimum spin coating time was then tested in a ring cavity laser. Phase shifting performance was observed at lasing threshold of 40 mW and maximum pump power of

100 mW. The wavelength coefficient obtained was 0.066 nm/mW and 0.057 nm/mW, respectively. This is because stronger gain from higher laser pump power has produced a stronger mode competition. From the results obtained, it is proven that WO_3 can be used in phase shifter as it can induce thermo-optic effect. This work had offered advantage which cannot be offered by non-fiber phase shifter which it has a compact setup to suit current need in communication field.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

TUNGSTEN TRIOKSIDA BERSEPADU SEMUA GENTIAN PENGANJAK FASA

Oleh

NORHANIE BINTI BAHTIAR AFFENDY

Oktober 2021

Pengerusi : Muhammad Hafiz bin Abu Bakar, PhD
Fakulti : Kejuruteraan

Penganjak fasa semua gentian adalah merupakan salah satu komponen penting dalam sistem komunikasi optik dan sistem pemprosesan isyarat. Tambahan pula, penganjak fasa semua gentian menawarkan penggunaan dalam sistem elektro-optik, gentian laser dan penderia. Binaan semua gentian adalah menarik kerana mempunyai keistimewaan seperti mudah untuk digandingkan dan rendah dalam kehilangan sisipan. Selain daripada itu, ia juga mempunyai pembungkusan yang padat dan kebolehan digunakan secara kawalan jauh. Kelemahan tidak linear gentian konvensional memerlukan penggunaan gentian yang panjang untuk membolehkan pertukaran fasa dilakukan. Cara lain untuk mendapatkan pertukaran fasa termasuklah memperkenalkan gangguan kedalam gentian melalui perubahan bentuk mekanikal dan juga kesan akousto-optik. Terdapat juga usaha dalam membangunkan penganjak fasa menggunakan modul fasa optik tidak linear melalui modul fasa-silang dan serakan Brillouin yang dirangsang. Baru-baru ini, pengkaji menemui kaedah lain iaitu menggunakan kesan haba dari bahan nano yang dilekatkan diatas gentian optik tirus. Kajian terdahulu memperkenalkan penggunaan bahan nano seperti fosforus hitam, grafin dan nanorod emas yang menunjukkan prestasi yang bagus. Kerja ini memfokuskan kepada pembinaan penganjak fasa gentian optik tirus yang dienap dengan tungsten trioksida (WO_3), bahan nano yang terkini dikaji dalam pelbagai aplikasi optik. Profil tirus yang digunakan sepanjang eksperimen adalah kepanjangan atas dan bawah tirus 5 mm, panjang pinggang gentian 10 mm dan lebar pinggang gentian 12 µm. Tungsten trioksida (WO_3) disintesis dengan mencampurkan larutan WO_3 dengan polidimetilsiloksina (PDMS). Kepekatan WO3 adalah tetap iaitu 5mg/mL untuk semua masa salutan putaran bermula dari 30 s sehngga 150 s dengan selang waktu 30 s setiap satu. Keberkesanan proses pemendapan bahan nano ditentukan oleh spektrometer UV Vis, mikroskop pengimbas elektron emisi medan, analisis penyebaran tenaga sinar-X, mikroskop daya atom dan spektroskopi RAMAN. Bagi mengenal pasti ciri-ciri penganjak fasa, kuasa pam divariasikan mulai dari 0 hingga 220 mW dengan selang kuasa 20 mW setiap satu. Ketebalan salutan ditemui sebagai satu

faktor yang mempengaruhi kebolehan WO_3 dalam mewujudkan pertukaran fasa. Anjakan biru pada pertukaran fasa maksimum iaitu 2.52π dan keberkesanan pertukaran spektra adalah 0.011 π/mW telah diperolehi untuk tungsten trioksida integrasi penganjak fasa semua gentian dengan masa putaran salutan 120 s. Penganjak fasa dengan masa putaran salutan paling optimum tersebut dikaji di dalam laser berkaviti bulat. Tahap keberkesanan penganjak fasa diperhatikan pada ambang laser di 40 mW dan kuasa pam maksimum iaitu 100 mW. Keberkesanan panjang gelombang diperolehi adalah 0.066 nm/mW dan 0.057 nm/mW. Ini adalah kerana gandaan yang lebih kuat terhasil daripada kuasa pam laser yang tinggi meyebabkan persaingan mod. Daripada dapatan keputusan, terbukti bahawa WO_3 boleh digunakan sebagai penganjak fasa kerana ia mampu untuk mewujudkan kesan termo-optik. Kerja ini menawarkan keistimewaan yang tidak dapat ditawarkan oleh binaan bukan serat termasuklah mempunyai binaan padat bagi memnuhi keperluan bidang komunikasi.

ACKNOWLEDGEMENTS

Alhamdulillah, all praise to the Almighty God that I am able to complete this thesis. Along this adventurous journey, I have truly met a lot of wonderful person who I can be thank to.

First of all, I would like express my thankfulness to my family which are my dad, Bahtiar Affendy Mashod also my beautiful mum, Siti Haidah Ali, who had continuously giving me support, cheering also encouraging me to really have faith and keeping me motivated along the journey. And to my other fellow family member, thank you for all of tremendous love and support to me.

I would like to express my greatest appreciation also gratitude to my awesome supervisor, Associate Professor Muhammad Hafiz Abu Bakar for always provide outstanding discussion and sharing his knowledge. Plus, he continuously being a very handy supervisor along the journey of this research. From the research work, I have truly gained a lot new knowledge especially how to really participate in the work. Not only that, I also have gain lots of good research ideas but also about life. My gratitude is also extends to my super supportive co-supervisors, Dr Nadiah Husseini Zainol Abidin and Dr Farah Diana Muhammad for their continuous help and guidance.

I would like to express my thanks to Dr Yasmin Mustapha Kamil, Noor Zirwatul Ahlam and Muhammad Amir Waluiddin Abdul Halim for always provide me the with strong supportive environment in conducting the research work also keep supporting me through this thesis writing journey. In addition, I would also like to give out my special thanks to Maisarah Mansur, Aishah Maisarah Burhanuddin and Mahzan Muhamad for their constant moral support also for always being there along this tough journey. Not to forget, Mr Zamili who has always being there to fulfill my need while conducting the research work.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree Master of Science. The members of the Supervisory Committee were as follows:

Muhammad Hafiz Abu Bakar, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairperson)

Nadiah Husseini Zainol Abidin, PhD
Senior Lecturer
Centre of Foundation Studies for Agricultural Science
Universiti Putra Malaysia
(Member)

Farah Diana Muhammad, PhD
Senior Lecturer
Faculty of Science
Universiti Putra Malaysia
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 9 March 2023

Declaration by Graduate Student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ____________________________ Date: ____________________________

Name and Matric No.: Norhanie binti Bahtiar Affendy

Declaration by Members of Supervisory Committee

This is to confirm that:

- The research conducted and the writing of this thesis was under our supervision;
- Supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ____
Name of Chairman of Supervisory Committee: Assoc. Prof. Dr. Muhammad Hafiz Abu Bakar

Signature: ____
Name of Member of Supervisory Committee: Dr. Nadiah Husseini Zainol Abidin

Signature: ____
Name of Member of Supervisory Committee: Dr. Farah Diana Muhammad

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

AFM	Atomic Force Microscope
AIN	Adaptive Instance Normalization
ASE	Amplified Spontaneous Emission
AuNPs	Gold Nanoparticles
BP	Black Phosphorus
C-band	Conventional-wavelength band (1530 nm to 1565 nm)
EDF	Erbium-Doped Fiber
EW	Evanescent Waves
FESEM	Field Emission Scanning Electron Microscopy
FSR	Free Spectral Range
GNR	Gold Nanorod
HCGs	High index Contrast Gratings
ITO	Indium-Tin-Oxide
LDM	Low Dimensional Material
NaCl	Sodium Chloride
NIR	Near Infra-Red
OPM	Optical Power Meter
OSA	Optical Spectrum Analyzer
PDMS	Polydimethylsiloxane
PST	Phase Shifting Transformer
RI	Refractive Index
RF	Radio Frequency
SMF	Single Mode Fiber
SBS	Stimulated Brillouin Scattering

SOI	Silicon-On-Insulator
TMDs	Transition Metal Dichalcogenides
TiN	Titanium Nitride
WDM	Wavelength Division Multiplexer
WO_3	Tungsten Trioxide

CHAPTER 1

INTRODUCTION

1.1 Overview

Phase shifter is a device that is used in communication systems to change the phase of an incoming signal, which is an important element in applications such as signal processing and laser beam combining [1] [2]. It works by introducing a small amount of delay into the incoming signal and mix it back with the original signal (without delay) at a certain frequency thus resulting in interference [3]. Phase shifter can be classified as either analog or digital device [4]. Analog tuning phase shifter controlled by tuning voltage level while digital phase shifter controlled via computer interface [5].

Optical phase shifter comes in various forms including free space [6] and waveguide device [7] [8]. As optical communication employs mainly optical fiber as transmission medium, the introduction of all-fiber phase shifter is handy because of their advantages such as coupling simplicity [9], polarization insensitivity [10], and low loss [11]. All-fiber phase shifter can be implemented into various devices such as wavelength-division multiplexing (WDM) fiber communication as well as fiber laser generation [12]. A common method to achieve phase shifting in optical fiber is by using the nonlinearity of the fiber itself but the drawback of this method is it needs either a special nonlinear fiber or a long conventional fiber thus making it inconvenient to use in small device [2]. In order to address this drawback, the all-fiber phase shifter is improved to work based on various techniques such as mechanical deformation [13], acousto-optic [7], electro-optic [9] and also thermo-optic effects [14]. Recent studies have looked into the use of thermo-optic effect due to its lower energy consumption in comparison to other effects [15]. Fundamental theory of thermo-optic effect works based on the injection of pump light that act as energy supply to thermo-optic element and induce refractive index (RI) changes [16] [17] [18].

Researchers have also investigated the concept of doping the fiber with either transition metal ions, rare earths or color center which will help in altering the RI via pump-induced thermal effect or ground state depletion [14]. A simpler method would be to employ tapered optical fiber coated with suitable nanomaterial as phase shifting transducer. The excitation of evanescence wave facilitates interaction with the surrounding material along the tapered region leading to change in temperature and RI that is subsequently reflected in terms of phase shift [19]. Nanomaterials that have been tested for this scheme include graphene and bismuthene [10] [20]. This approach has shown remarkable output in obtaining shorter rise and fall time compared to conventional phase shifter that use non-fiber waveguide configuration instead of all-fiber configuration [21].

1.2 Problem Statement

All-fiber phase shifters based on the integration of tapered optical fiber and nanomaterial are the current trend thanks to its promising performance and fabrication simplicity. Despite the potential, the aim is still to obtain a significant phase shifting effect from the employed nanomaterial. Additionally, nanomaterials employed in all-fiber phase shifter have exhibited susceptibility to external perturbations and incur additional loss due their wide range of absorption wavelength. Some nanomaterials such as bismuthene and boron require complicated fabrication process before it can be utilized as phase shifter. Therefore, continuous effort is still given to find feasible nanomaterials that can be integrated in all-fiber phase shifter. The performance of nanomaterial phase shifter in tunable fiber laser is also a point of investigation considering the constant interest in fiber laser.

1.3 Aim and Objectives

The research work is focused on integrating tungsten trioxide (WO_3) in all-fiber phase shifter. The significance of depositing the nanomaterial on tapered fiber lies in the capability of WO_3 to generate thermo-optic effect leading to phase shifts. The objectives of the study are:

i. To fabricate an all-fiber phase shifter based on tapered fiber with WO_3 coating.
ii. To characterize the performance of the fabricated phase shifter.
iii. To design a tunable fiber laser based on the fabricated phase shifter.

1.4 Scope of Work

The scope of work in this research is summarized in Figure 1.1. Basically, the study is focused on the design and development of phase shifter, an integral component in optical communication system. The all-fiber optical phase shifter is favored because of qualities such as seamless integration and low loss polarization insensitivity. Nanomaterial was introduced to assist in enhancing phase shifting effect. Tungsten trioxide is used for this work because of the ability to absorb near-infrared (NIR) light also efficient in the conversion of light-to-heat properties. Beside that, it has high mechanical strength and adequate thermal also chemical stability. Nanomaterial is the agent in delivering thermo-optic effect through temperature-induced RI changes. Although it is known that the phase shifting based on thermo-optic effect can be induced in the material, it is difficult to measure the exact temperature of the phase shifter during the operation due to the lack of proper equipment. The other limitation of the all-fiber phase shifter using nanomaterial is that the fabrication proves might take up time and the material itself is quite expensive. Lastly, considerations have to be given to the external factor such as temperature fluctuation that can also effect the phase shifter performance.

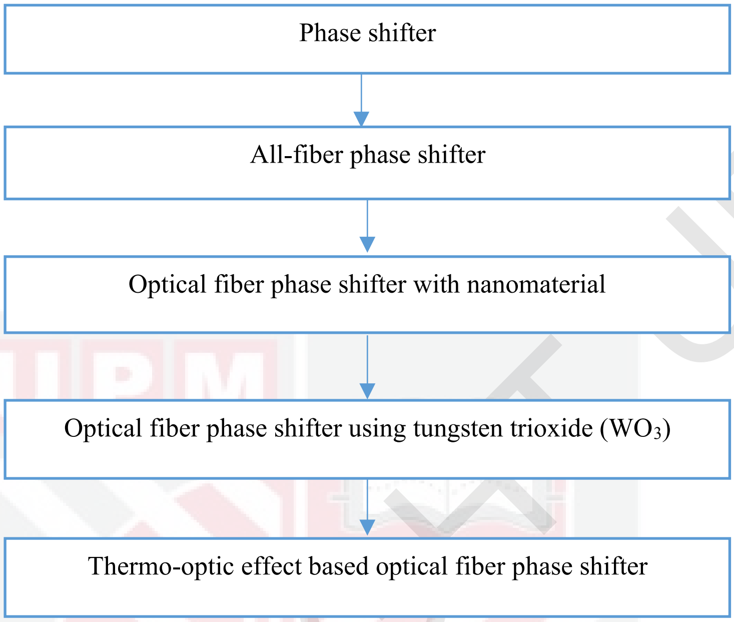

Figure 1.1: Scope of Work

1.5 Organization of Thesis

The organization of the thesis is explained as following:

Chapter 1 consists of the introduction and overview of the research work. It provides a brief background on optical fiber phase shifter and its current applications. The challenges related to all-fiber phase shifter is highlighted along with the aim and objectives of this work. The scope of work and thesis organization are also included in this chapter.

Chapter 2 describes the fundamental theory related to phase shifter, especially all-fiber phase shifter. The rise of nanomaterial usage in all-fiber phase shifter is also discussed in this chapter. Relevant past studies are cited and reviewed to elucidate the position of this work in the current research field.

Chapter 3 elucidates the methodology used throughout the research together with the results gained from the experimental work. The experimental design and rationale of each stage of work starting with taper fabrication until the final tunable laser design are also discussed. The results are presented in the forms of images and graphs alongside their analysis.

Finally, chapter 4 concludes the whole research work. All the important findings correlated to the earlier objectives are highlighted and some recommendations for future work are also inserted here.

REFERENCES

[1] R. W. Heath, N. González-Prelcic, S. Rangan, W. Roh, and A. M. Sayeed, "An Overview of Signal Processing Techniques for Millimeter Wave MIMO Systems," *IEEE Journal of Selected Topics in Signal Processing,* vol. 10, no. 3, pp. 436-453, 2016.

[2] X. Yang, Q. Long, Z. Liu, Y. Zhang, J. Yang, D. Kong, L. Yuan, and K. Oh, "Microfiber interferometer integrated with Au nanorods for an all-fiber phase shifter and switch," *Optics Letters,* vol. 44, no. 5, pp. 1092-1095, 2019/03/01 2019.

[3] P. Brown, "Chapter 2 - Fundamentals of Audio and Acoustics," in *Handbook for Sound Engineers (Fourth Edition)*, G. M. Ballou, Ed. Oxford: Focal Press, 2008, pp. 21-39.

[4] S. S. A. Abbas, K. L. Priya, and M. Lavanya, "Analysis Of Phase Shifter In Analog And Digital Domain," in *2019 3rd International Conference on Computing and Communications Technologies (ICCCT)*, 2019, pp. 232-236.

[5] V. Nasserddine, "Millimeter-wave phase shifters based on tunable transmission lines in MEMS technology post-CMOS process," 2016.

[6] A. V. Zvyagin and D. D. Sampson, "Achromatic optical phase shifter–modulator," *Optics Letters,* vol. 26, no. 4, pp. 187-189, 2001/02/15 2001.

[7] E. Li, J. Yao, D. Yu, J. Xi, and J. Chicharo, "Optical phase shifting with acousto-optic devices," *Optics Letters,* vol. 30, no. 2, pp. 189-191, 2005/01/15 2005.

[8] L. Lucchetti, K. Kushnir, A. Zaltron, and F. Simoni, "Light controlled phase shifter for optofluidics," *Optics Letters,* vol. 41, no. 2, pp. 333-335, 2016/01/15 2016.

[9] O. Tarasenko and W. Margulis, "Electro-optical fiber modulation in a Sagnac interferometer," *Optics Letters,* vol. 32, no. 11, pp. 1356-1358, 2007/06/01 2007.

[10] Z. Liu, Y. Meng, H. Xiao, L. Deng, X. Guo, G. Liu, Y. Tian, and J. Yang, "Graphene-assisted all-optical tunable Mach–Zehnder interferometer based on microfiber," *Optics Communications,* vol. 428, pp. 77-83, 2018.

[11] T.-Y. Kim, M. Hanawa, S.-J. Kim, S. Hann, Y. H. Kim, W.-T. Han, and C.-S. Park, "Optical delay interferometer based on phase shifted fiber Bragg grating with optically controllable phase shifter," *Optics Express,* vol. 14, no. 10, pp. 4250-4255, 2006/05/15 2006.

[12] G. E. Town, "Lasers, Optical Fiber," in *Encyclopedia of Physical Science and Technology (Third Edition)*, R. A. Meyers, Ed. New York: Academic Press, 2003, pp. 419-441.

[13] A. Bhatti, H. S. Al-Raweshidy, and G. Murtaza, "Optical antenna using D-fibre for radio-over-fibre applications," *Optical Fiber Technology,* vol. 8, no. 2, pp. 153-161, 2002/04/01/ 2002.

[14] X. Gan, C. Zhao, Y. Wang, D. Mao, L. Fang, L. Han, and J. Zhao, "Graphene-assisted all-fiber phase shifter and switching," *Optica,* vol. 2, no. 5, p. 468, 2015.

[15] Z. Shao, C. Wang, K. Wu, H. Zhang, and J. Chen, "Fiber all-optical light control with low-dimensional materials (LDMs): thermo-optic effect and saturable absorption," *Nanoscale Advances,* vol. 1, no. 11, pp. 4190-4206, 2019.

[16] S. Korposh, S. W. James, S. W. Lee, and R. P. Tatam, "Tapered Optical Fibre Sensors: Current Trends and Future Perspectives," *Sensors (Basel),* vol. 19, no. 10, May 17 2019.

[17] N. C. Harris, Y. Ma, J. Mower, T. Baehr-Jones, D. Englund, M. Hochberg, and C. Galland, "Efficient, compact and low loss thermo-optic phase shifter in silicon," (in eng), *Optics express,* vol. 22, no. 9, pp. 10487-10493, 2014/05// 2014.

[18] S. Zhu, T. Hu, Z. Xu, Y. Dong, Q. Zhong, Y. Li, and N. Singh, "An Improved Thermo-Optic Phase Shifter with AlN Block for Silicon Photonics," in *Optical Fiber Communication Conference (OFC) 2019*, San Diego, California, 2019, p. M1C.5: Optical Society of America.

[19] S. Korposh, S. W. James, S.-W. Lee, and R. P. Tatam, "Tapered Optical Fibre Sensors: Current Trends and Future Perspectives," (in eng), *Sensors (Basel, Switzerland),* vol. 19, no. 10, p. 2294, 2019.

[20] K. Wang, J. Zheng, H. Huang, Y. Chen, Y. Song, J. Ji, and H. Zhang, "All-optical signal processing in few-layer bismuthene coated microfiber: towards applications in optical fiber systems," *Opt Express,* vol. 27, no. 12, pp. 16798-16811, Jun 10 2019.

[21] K. Wu, C. Guo, H. Wang, X. Zhang, J. Wang, and J. Chen, "All-optical phase shifter and switch near 1550nm using tungsten disulfide (WS2) deposited tapered fiber," *Optics Express,* vol. 25, no. 15, pp. 17639-17649, 2017/07/24 2017.

[22] R. Verma, A. Sharma, and B. Gupta, "Surface plasmon resonance based tapered fiber optic sensor with different taper profiles," *Optics Communications - OPT COMMUN,* vol. 281, pp. 1486-1491, 03/01 2008.

[23] Y. Jung, G. Brambilla, and D. J. Richardson, "Comparative study of the effective single mode operational bandwidth in sub-wavelength optical wires and conventional single-mode fibers," *Optics Express,* vol. 17, no. 19, pp. 16619-16624, 2009/09/14 2009.

[24] Y. Velankar and S. Mehdi, "Tapered Optical Fiber for WDM Applications," *Proc SPIE,* vol. 5260, pp. 298-302, 12/01 2003.

[25] J. Kerttula, V. Filippov, Y. Chamorovskii, V. Ustimchik, K. Golant, and O. G. Okhotnikov, "Principles and performance of tapered fiber lasers: from uniform to flared geometry," *Applied Optics,* vol. 51, no. 29, pp. 7025-7038, 2012/10/10 2012.

[26] K. Q. Kieu and M. Mansuripur, "Biconical Fiber Taper Sensors," *IEEE Photonics Technology Letters,* vol. 18, no. 21, pp. 2239-2241, 2006.

[27] J. M. Corres, F. J. Arregui, and I. R. Matias, "Design of Humidity Sensors Based on Tapered Optical Fibers," *Journal of Lightwave Technology,* vol. 24, no. 11, pp. 4329-4336, 2006/11/01 2006.

[28] M. Sumetsky, Y. Dulashko, and A. Hale, "Fabrication and study of bent and coiled free silica nanowires: Self-coupling microloop optical interferometer," *Optics Express,* vol. 12, no. 15, pp. 3521-3531, 2004/07/26 2004.

[29] B. Musa, Y. Mustapha Kamil, M. H. Abu Bakar, A. S. M. Noor, A. Ismail, and M. A. Mahdi, "Effects of taper parameters on free spectral range of non-adiabatic tapered optical fibers for sensing applications," *Microwave and Optical Technology Letters,* vol. 58, no. 4, pp. 798-803, 2016.

[30] J. Colás, *Dual-Mode Electro-photonic Silicon Biosensors*. 2017.

[31] Y. Mustapha, M. H. Abu Bakar, M. Mustapa, M. Yaacob, A. Syahir, and M. A. Mahdi, "Sensitive and Specific Protein Sensing Using Single-Mode Tapered Fiber Immobilized With Biorecognition Molecules," *IEEE Photonics Journal,* vol. 7, pp. 1-1, 12/01 2015.

[32] G. D'Amato, G. Avitabile, G. Coviello, and C. Talarico, "DDS-PLL Phase Shifter Architectures for Phased Arrays: Theory and Techniques," *IEEE Access,* vol. 7, pp. 19461-19470, 2019.

[33] H. J. Qian, B. Zhang, and X. Luo, "High-Resolution Wideband Phase Shifter With Current Limited Vector-Sum," *IEEE Transactions on Circuits and Systems I: Regular Papers,* vol. 66, no. 2, pp. 820-833, 2019.

[34] N. Marinho, Y. Phulpin, A. Atayi, and M. Hennebel, "Modeling Phase Shifters in Power System Simulations Based on Reduced Networks," *Energies,* vol. 12, no. 11, p. 2167, 2019.

[35] A. Pandey and S. K. Selvaraja, "Broadly tunable and low power penalty radio frequency phase shifter using a coupled silicon microcavity," *Appl Opt,* vol. 59, no. 2, pp. 425-432, Jan 10 2020.

[36] Y.-P. Lyu, L. Zhu, and C.-H. Cheng, "Design and Analysis of Schiffman Phase Shifter Under Operation of its Second Phase Period," *IEEE Transactions on Microwave Theory and Techniques,* vol. 66, no. 7, pp. 3263-3269, 2018.

[37] A. V. Zvyagin and D. D. Sampson, "Achromatic optical phase shifter-modulator," *Optics Letters,* Article vol. 26, no. 4, pp. 187-189, 2001.

[38] D. Dai, Y. Tang, and J. E. Bowers, "Mode conversion in tapered submicron silicon ridge optical waveguides," *Optics Express,* vol. 20, no. 12, pp. 13425-13439, 2012/06/04 2012.

[39] S. Rajput, V. Kaushik, S. Jain, and M. Kumar, "Slow Light Enhanced Phase Shifter Based on Low-Loss Silicon-ITO Hollow Waveguide," *IEEE Photonics Journal,* vol. 11, no. 1, pp. 1-8, 2019.

[40] Z. Li, H. Chen, J. Wang, H. Lu, and C. Liu, "Compact design of an optical phase shifter packaged with IST microheater used for integrated photonics," *Results in Physics,* vol. 19, p. 103644, 2020/12/01/ 2020.

[41] R. He, P. J. A. Sazio, A. C. Peacock, N. Healy, J. R. Sparks, M. Krishnamurthi, V. Gopalan, and J. V. Badding, "Integration of gigahertz-bandwidth semiconductor devices inside microstructured optical fibres," *Nature Photonics,* vol. 6, no. 3, pp. 174-179, 2012/03/01 2012.

[42] G. P. Agrawal, "Nonlinear Effects in Optical Fibers," in *Encyclopedia of Materials: Science and Technology*, K. H. J. Buschow, R. W. Cahn, M. C. Flemings, B. Ilschner, E. J. Kramer, S. Mahajan *et al.*, Eds. Oxford: Elsevier, 2001, pp. 6218-6226.

[43] F. S. F. Mário, "Nonlinear effects in optical fibers: limitations and benefits," in *Proc.SPIE*, 2008, vol. 6793.

[44] V. A. Vardanyan, "Effect of self-phase modulation and cross-phase modulation on OFDM signals in fibre-optic access networks," *Quantum Electronics,* vol. 48, no. 4, pp. 395-400, 2018/04/26 2018.

[45] S. Yu, X. Wu, K. Chen, B. Chen, X. Guo, D. Dai, L. Tong, W. Liu, and Y. Ron Shen, "All-optical graphene modulator based on optical Kerr phase shift," *Optica,* vol. 3, no. 5, p. 541, 2016.

[46] M. Pohanka, "The Piezoelectric Biosensors: Principles and Applications, a Review," *International Journal of Electrochemical Science,* vol. 12, pp. 496-506, 01/01 2017.

[47] F. De Lucia and P. J. A. Sazio, "Thermal Poling of Optical Fibers: A Numerical History," *Micromachines (Basel),* vol. 11, no. 2, Jan 27 2020.

[48] G. Coppola, L. Sirleto, I. Rendina, and M. Iodice, "Advance in thermo-optical switches: Principles, materials, design, and device structure," *Optical Engineering - OPT ENG,* vol. 50, 07/01 2011.

[49] W. Wenyuan, Y. Yongqin, G. Youfu, and L. Xuejin, "Measurements of thermo-optic coefficient of standard single mode fiber in large temperature range," in *Proc.SPIE*, 2015, vol. 9620.

[50] "Chapter 3 - Thermo-Optic Coefficients," in *Handbook of Optical Constants of Solids,* E. D. Palik, Ed. Burlington: Academic Press, 1997, pp. 115-261.

[51] M. Mendez-Astudillo, M. Okamoto, Y. Ito, and T. Kita, "Compact thermo-optic MZI switch in silicon-on-insulator using direct carrier injection," *Opt Express,* vol. 27, no. 2, pp. 899-906, Jan 21 2019.

[52] H. Gao, Y. Jiang, Y. Cui, L. Zhang, J. Jia, and L. Jiang, "Investigation on the Thermo-Optic Coefficient of Silica Fiber Within a Wide Temperature Range," *Journal of Lightwave Technology,* vol. 36, no. 24, pp. 5881-5886, 2018.

[53] G. Adamovsky, S. F. Lyuksyutov, J. R. Mackey, B. M. Floyd, U. Abeywickrema, I. Fedin, and M. Rackaitis, "Peculiarities of thermo-optic coefficient under different temperature regimes in optical fibers containing fiber Bragg gratings," *Optics Communications,* vol. 285, no. 5, pp. 766-773, 2012/03/01/ 2012.

[54] R. M. Waxler and G. W. Cleek, "Refractive indices of fused silica at low temperatures," *Journal of Research of the National Bureau of Standards Section A: Physics and Chemistry,* p. 279, 1971.

[55] S. S. Kurtz, S. Amon, and A. Sankin, "Effect of Temperature on Density and Refractive Index," *Industrial & Engineering Chemistry,* vol. 42, no. 1, pp. 174-176, 1950/01/01 1950.

[56] K. T. Kim, I. S. Kim, C. H. Lee, and J. Lee, "A temperature-insensitive cladding-etched Fiber Bragg grating using a liquid mixture with a negative thermo-optic coefficient," *Sensors (Basel),* vol. 12, no. 6, pp. 7886-92, 2012.

[57] A. Kersey, M. A. Davis, H. Patrick, M. Leblanc, K. Koo, C. G. Askins, M. Putnam, and E. Friebele, "Fiber Grating Sensors," *Lightwave Technology, Journal of,* vol. 15, pp. 1442-1463, 09/01 1997.

[58] O. Frazão, J. M. Baptista, J. L. Santos, J. Kobelke, and K. Schuster, "Refractive index tip sensor based on Fabry-Perot cavities formed by a suspended core fibre," *Journal of the European Optical Society - Rapid publications; Vol 4 (2009),* 2009.

[59] B. Musa, Y. Mustapha Kamil, M. H. Abu Bakar, A. S. Mohd Noor, A. Ismail, and M. A. Mahdi, "Investigating the Effect of Taper Length on Sensitivity of the Tapered-Fiber Based Temperature Sensor," *Jurnal Teknologi,* vol. 78, no. 3, 2016.

[60] R. C. Kamikawachi, I. Abe, A. S. Paterno, H. J. Kalinowski, M. Muller, J. L. Pinto, and J. L. Fabris, "Determination of thermo-optic coefficient in liquids with fiber Bragg grating refractometer," *Optics Communications,* vol. 281, no. 4, pp. 621-625, 2008/02/15/ 2008.

[61] Y. Zhao, A. Dunn, J. Lin, and D. Shi, "Chapter 13 - Photothermal Effect of Nanomaterials for Efficient Energy Applications," in *Novel Nanomaterials for Biomedical, Environmental and Energy Applications*, X. Wang and X. Chen, Eds.: Elsevier, 2019, pp. 415-434.

[62] R. Chu, C. Guan, Y. Bo, J. Liu, J. Shi, J. Yang, P. Ye, P. Li, J. Yang, and L. Yuan, "Graphene decorated twin-core fiber Michelson interferometer for all-optical phase shifter and switch," *Optics Letters,* vol. 45, no. 1, pp. 177-180, 2020/01/01 2020.

[63] M. Luo, X. Yang, P. Teng, D. Kong, Z. Liu, D. Gao, Z. Li, X. Wen, L. Yuan, K. Li, and N. Copner, "All-fiber spectral modulating device based on microfiber interferometer grown with tungsten disulfide," *Instrumentation Science & Technology,* vol. 48, pp. 1-13, 03/12 2020.

[64] Y. Wang, F. Zhang, X. Tang, X. Chen, Y. Chen, W. Huang, Z. Liang, L. Wu, Y. Ge, Y. Song, J. Liu, D. Zhang, J. Li, and H. Zhang, "All-Optical Phosphorene Phase Modulator with Enhanced Stability Under Ambient Conditions," *Laser & Photonics Reviews,* vol. 12, no. 6, p. 1800016, 2018.

[65] Y. Wang, W. Huang, J. Zhao, H. Huang, C. Wang, F. Zhang, J. Liu, J. Li, M. Zhang, and H. Zhang, "A bismuthene-based multifunctional all-optical phase and intensity modulator enabled by photothermal effect," *Journal of Materials Chemistry C,* vol. 7, no. 4, pp. 871-878, 2019.

[66] L. Shen, F. Gao, L. Gan, L. Huo, S. Fu, H. Liu, and M. Tang, "All-optical Phase Shifter and Switch Based on Microfiber Coated with Colloidal Quantum Dots," in *2018 Asia Communications and Photonics Conference (ACP)*, 2018, pp. 1-2.

[67] Q. Guo, K. Wu, Z. Shao, E. T. Basore, P. Jiang, and J. Qiu, "Boron Nanosheets for Efficient All-Optical Modulation and Logic Operation," *Advanced Optical Materials,* https://doi.org/10.1002/adom.201900322 vol. 7, no. 13, p. 1900322, 2019/07/01 2019.

[68] Q. Wu, W. Huang, Y. Wang, C. Wang, Z. Zheng, H. Chen, and M. Zhang, "All-Optical Control of Microfiber Knot Resonator Based on 2D Ti2CTx MXene," *Advanced Optical Materials,* vol. 8, 01/20 2020.

[69] R. Liu and W. Li, "High-Thermal-Stability and High-Thermal-Conductivity Ti3C2Tx MXene/Poly(vinyl alcohol) (PVA) Composites," *ACS Omega,* vol. 3, no. 3, pp. 2609-2617, 2018/03/31 2018.

[70] R. Li, L. Zhang, L. Shi, and P. Wang, "MXene Ti3C2: An Effective 2D Light-to-Heat Conversion Material," *ACS Nano,* vol. 11, no. 4, pp. 3752-3759, 2017/04/25 2017.

[71] M. Luo, X. Yang, P. Teng, Z. Liu, D. Kong, J. Zhang, J. Yang, F. Tian, D. Gao, Z. Li, L. Yuan, K. Li, and N. Copner, "All-fiber phase shifter based on hollow fiber interferometer integrated with Au nanorods," *Sensors and Actuators A: Physical,* vol. 301, p. 111750, 2020.

[72] M. Luo, X. Yang, P. Teng, Z. Liu, J. Yang, D. Kong, D. Gao, Z. Li, X. Wen, X. Yu, L. Yuan, K. Li, M. Bowkett, N. Copner, and X. Wang, "All-fiber phase modulator and switch based on local surface plasmon resonance effect of the gold nanoparticles embedded in gel membrane," *Appl Opt,* vol. 59, no. 33, pp. 10506-10511, Nov 20 2020.

[73] C. Mardare and A. W. Hassel, "Review on the Versatility of Tungsten Oxide Coatings," *physica status solidi (a),* vol. 216, 04/01 2019.

[74] P. A. Shinde and S. C. Jun, "Review on Recent Progress in the Development of Tungsten Oxide Based Electrodes for Electrochemical Energy Storage," *ChemSusChem,* https://doi.org/10.1002/cssc.201902071 vol. 13, no. 1, pp. 11-38, 2020/01/09 2020.

[75] C.-M. Wu, S. Naseem, M.-H. Chou, J.-H. Wang, and Y.-Q. Jian, "Recent Advances in Tungsten-Oxide-Based Materials and Their Applications," *Frontiers in Materials,* vol. 6, 2019.

[76] F. Gao, Y. Wang, L. Xu, Z. Feng, Q. Wu, B. Zhang, J. Liu, J. Tang, M. Tang, H. Liu, S. Fu, Y. Ruan, H. Ebendorff-Heidepriem, and D. Liu, "Light-controllable fiber interferometer utilizing photoexcitation dynamics in colloidal quantum dot," *Opt Express,* vol. 26, no. 4, pp. 3903-3914, Feb 19 2018.

[77] M. Luo, X. Yang, P. Teng, D. Kong, Z. Liu, D. Gao, Z. Li, X. Wen, L. Yuan, K. Li, and N. Copner, "All-fiber spectral modulating device based on microfiber interferometer grown with tungsten disulfide," *Instrumentation Science & Technology,* vol. 48, no. 5, pp. 505-517, 2020/09/02 2020.

[78] Q. Wu, S. Chen, Y. Wang, L. Wu, X. Jiang, F. Zhang, X. Jin, Q. Jiang, Z. Zheng, J. Li, and M. Zhang, "MZI-Based All-Optical Modulator Using MXene Ti 3 C 2 T x (T = F, O, or OH) Deposited Microfiber," *Advanced Materials Technologies,* vol. 4, p. 1800532, 01/04 2019.

[79] Y. M. Kamil, M. H. A. Bakar, A. Syahir, and M. A. Mahdi, "Determining salinity using a singlemode tapered optical fiber," in *2014 IEEE 5th International Conference on Photonics (ICP)*, 2014, pp. 223-226.

[80] M. A. W. Abdul Hadi, K. Y. Lau, N. H. Zainol Abidin, S. O. Baki, E. K. Ng, L. H. Kee, and M. A. Mahdi, "Investigation of tungsten trioxide as a saturable absorber for mode-locked generation," *Optics & Laser Technology,* vol. 132, p. 106496, 2020/12/01/ 2020.

[81] L. Xu, M.-L. Yin, and S. Liu, "Agx@WO3 core-shell nanostructure for LSP enhanced chemical sensors," *Scientific Reports,* vol. 4, no. 1, p. 6745, 2014/10/23 2014.

[82] S. Pradhan, J. Hedberg, E. Blomberg, S. Wold, and I. Odnevall Wallinder, "Effect of sonication on particle dispersion, administered dose and metal release of non-functionalized, non-inert metal nanoparticles," *Journal of Nanoparticle Research,* vol. 18, no. 9, p. 285, 2016/09/22 2016.

[83] D. Coetzee, M. Venkataraman, J. Militky, and M. Petru, "Influence of Nanoparticles on Thermal and Electrical Conductivity of Composites," *Polymers (Basel),* vol. 12, no. 4, Mar 27 2020.

[84] S. V. Kamat, V. Puri, and R. K. Puri, "The Effect of Film Thickness on the Structural Properties of Vacuum Evaporated Poly(3-methylthiophene) Thin Films," *ISRN Polymer Science,* vol. 2012, p. 570363, 2012/03/21 2012.

[85] D. Kim, S. H. Kim, and J. Y. Park, "Floating-on-water Fabrication Method for Thin Polydimethylsiloxane Membranes," *Polymers (Basel),* vol. 11, no. 8, Jul 31 2019.

[86] H. Lee, S. Chang, and E. Yoon, "A Flexible Polymer Tactile Sensor: Fabrication and Modular Expandability for Large Area Deployment," *Journal of Microelectromechanical Systems,* vol. 15, no. 6, pp. 1681-1686, 2006.

[87] A. Nady, F. Baharom, A. Abdul Latiff, and S. W. Harun, "Mode-Locked Erbium-Doped Fiber Laser Using Vanadium Oxide as Saturable Absorber," *Chinese Physics Letters,* vol. 35, p. 044204, 04/01 2018.

[88] R. Radzali, A. A. Latif, A. W. Al-Alimi, M. A. Mahdi, and M. H. A. Bakar, "Highly Nonlinear Fiber-Assisted Multiwavelength Generation in Linear Cavity Thulium-Doped Fiber Laser," *IEEE Photonics Journal,* vol. 8, no. 5, pp. 1-7, 2016.

[89] Y. Yu, H. Chen, Z. Zhang, D. Chen, J. Wang, Z. Wei, J. Yang, and P. Yan, "Characteristic Test Analysis of Graphene Plus Optical Microfiber Coupler Combined Device and Its Application in Fiber Lasers," *Sensors,* vol. 20, no. 6, 2020.

[90] J. Kong, V. G. Lucivero, R. Jiménez-Martínez, and M. W. Mitchell, "Long-term laser frequency stabilization using fiber interferometers," *Review of Scientific Instruments,* vol. 86, no. 7, p. 073104, 2015/07/01 2015.