



**Broadband Dispersion Flattened Porous Core Photonic  
Crystal Fiber for Low Loss THz Wave Guiding**

by

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## TABLE OF CONTENTS

|                                | <b>PAGE</b> |
|--------------------------------|-------------|
| <b>THESIS DECLARATION</b>      | i           |
| <b>PERMISSION TO USE</b>       | ii          |
| <b>ACKNOWLEDGEMENT</b>         | iii         |
| <b>TABLE OF CONTENTS</b>       | iv          |
| <b>LIST OF TABLES</b>          | ix          |
| <b>LIST OF FIGURES</b>         | x           |
| <b>LIST OF ABBREVIATIONS</b>   | xv          |
| <b>LIST OF SYMBOLS</b>         | xvi         |
| <b>ABSTRAK</b>                 | xvii        |
| <b>ABSTRACT</b>                | xviii       |
| <b>CHAPTER I INTRODUCTION</b>  | 1           |
| 1.1 Introduction               | 1           |
| 1.2 Research Background        | 3           |
| 1.3 Problem Statement          | 5           |
| 1.4 Research Objectives        | 6           |
| 1.5 Scope of Work              | 7           |
| 1.6 Organization of the Thesis | 9           |

|   |           |
|---|-----------|
| <b>CHAPTER 2 LITERATURE REVIEW</b>                                  | <b>10</b> |
| 2.1 Introduction  | 10        |
| 2.2 Summary on Previously Reported Metallic & Dielectric Waveguides | 12        |
| 2.2.1 Metallic Waveguides   | 12        |
| 2.2.2 Dielectric Waveguides   | 14        |
| 2.3 Porous Core Fiber as THz Waveguides                             | 18        |
| 2.3.1 Materials for THz Waveguide                                   | 19        |
| 2.3.1.1 Properties of TOPAS Material                                | 21        |
| 2.3.2 Fabrication Process of Porous Core Waveguides                 | 23        |
| 2.3.3 Different Proposed Porous Core Waveguide Designs              | 25        |
| 2.3.3.1 Honeycomb Design  | 26        |
| 2.3.3.2 Polymer MOF Design  | 27        |
| 2.3.3.3 Porous Core Structure                                       | 28        |
| 2.3.3.4 Fabricated Honeycomb Fiber                                  | 29        |
| 2.3.3.5 High Birefringent (HB) Porous Fiber                         | 31        |
| 2.3.3.6 Octagonal Porous Core Design                                | 32        |
| 2.3.3.7 Hexagonal Waveguide Design                                  | 34        |
| 2.3.3.8 Triangular Lattice Design                                   | 35        |
| 2.3.3.9 Hybrid Porous Core Fiber                                    | 38        |
| 2.3.3.10 Octagonal Porous PCF                                       | 41        |
| 2.3.3.11 Spiral THz Fiber   | 43        |
| 2.3.3.12 Slotted Core Design  | 47        |
| 2.3.3.13 Rotated Core Waveguide Design                              | 51        |
| 2.3.4 Significant Discoveries in Last Decade                        | 56        |
| 2.4 Summary   | 59        |

|   |    |
|---|----|
| <b>CHAPTER 3 RESEARCH METHODOLOGY</b>         | 61 |
| 3.1 Introduction                              | 61 |
| 3.2 Description of Methodology                | 62 |
| 3.3 Design Methodology                        | 64 |
| 3.3.1 Design of Hybrid Core                   | 65 |
| 3.3.2 Design of Cladding                      | 67 |
| 3.3.3 Design of perfectly matched layer (PML) | 69 |
| 3.3.4 Designing Method for COMSOL             | 70 |
| 3.4 Simulation Methodology                    | 73 |
| 3.4.1 Simulation Method for COMSOL            | 73 |
| 3.4.2 Finite Element Method (FEM)             | 76 |
| 3.4.3 Simulation Method for MATLAB            | 77 |
| 3.5.1 Effective Refractive Index              | 77 |
| 3.5.2 Effective Material Loss (EML)           | 78 |
| 3.5.3 Confinement Loss                        | 79 |
| 3.5.4 Bending Loss                            | 79 |
| 3.5.5 Power Fraction                          | 80 |
| 3.5.6 Dispersion                              | 81 |
| 3.6 Comparison of Methodologies               | 82 |
| 3.7 Summary                                   | 84 |
| <b>CHAPTER 4 RESULTS AND DISCUSSION</b>       | 85 |
| 4.1 Introduction                              | 85 |
| 4.2 Proposed Design                           | 86 |
| 4.2.1 Air Hole Arrangement                    | 88 |
| 4.2.1.1 Cladding Air Hole Distribution        | 88 |

|         |  |     |
|---------|--|-----|
| 4.2.1.2 | Core Air Hole Distribution                       | 89  |
| 4.2.2   | Design Structure Using COMSOL                    | 90  |
| 4.3     | Simulation Results & Discussion                  | 93  |
| 4.3.1   | Guiding Properties for Optimum Design Parameters | 94  |
| 4.3.1.1 | Fundamental Mode Field Distribution              | 97  |
| 4.3.1.2 | Effective Refractive Index Profile               | 98  |
| 4.3.1.3 | Effective Material Loss (EML)                    | 100 |
| 4.3.1.4 | Confinement Loss                                 | 103 |
| 4.3.1.5 | Bending Loss                                     | 104 |
| 4.3.1.6 | Fraction of Power                                | 105 |
| 4.3.1.7 | Dispersion                                       | 106 |
| 4.3.2   | Design with 4 Hexagonal Rings in Cladding        | 110 |
| 4.3.2.1 | Design Structure Using COMSOL                    | 112 |
| 4.3.2.2 | Ideal Parameters for 4-Ring Cladding Design      | 113 |
| 4.3.2.3 | Fundamental Mode Fields for 8.38% Core Area      | 117 |
| 4.3.2.4 | Effective Refractive Index at 8.38% Core Area    | 118 |
| 4.3.2.5 | EML for 8.38% Core Area Design                   | 119 |
| 4.3.2.6 | Confinement Loss for 8.38% Core Area Design      | 120 |
| 4.3.2.7 | Bending Loss for 8.38% Core Area Design          | 121 |
| 4.3.2.8 | Fraction of Power for 8.38% Core Area Design     | 122 |
| 4.3.2.9 | Dispersion Properties for 8.38% Core Area Design | 122 |
| 4.3.3   | Design with 5 Hexagonal Rings in Cladding        | 124 |
| 4.3.3.1 | Design Structure Using COMSOL                    | 126 |
| 4.3.3.2 | Ideal Parameters for 5-Ring Cladding Design      | 127 |
| 4.3.3.3 | Fundamental Mode Fields for 2.70% Core Area      | 130 |

|                              |   |     |
|------------------------------|---|-----|
| 4.3.3.4                      | Effective Refractive Index at 2.70% Core Area         | 132 |
| 4.3.3.5                      | EML for 2.70% Core Area Design                        | 133 |
| 4.3.3.6                      | Confinement Loss for 2.70% Core Area Design           | 134 |
| 4.3.3.7                      | Bending Loss for 2.70% Core Area Design               | 135 |
| 4.3.3.8                      | Fraction of Power for 2.70% Core Area Design          | 136 |
| 4.3.3.9                      | Dispersion Properties for 2.70% Core Area Design      | 137 |
| 4.3.4                        | Impacts of Different Core Areas on Guiding Properties | 138 |
| 4.3.4.1                      | Comparison of Design Structure                        | 139 |
| 4.3.4.2                      | Comparison of Effective Refractive Index              | 142 |
| 4.3.4.3                      | Comparison of EML for Different Core Areas            | 144 |
| 4.3.4.4                      | Effect on Confinement Loss at Different Core Areas    | 145 |
| 4.3.4.5                      | Effect on Bending Loss at Different Core Areas        | 147 |
| 4.3.4.6                      | Comparison of Power Fraction                          | 148 |
| 4.3.4.7                      | Changes in Dispersion Properties                      | 151 |
| 4.4                          | Summary   | 154 |
| <b>CHAPTER 5 CONCLUSIONS</b> |   | 156 |
| 5.1                          | Conclusion  | 156 |
| 5.2                          | Research Contributions                                | 157 |
| 5.3                          | Special Feature                                       | 158 |
| 5.4                          | Significance of Work                                  | 158 |
| 5.5                          | Limitations of Work                                   | 159 |
| 5.6                          | Future Works  | 159 |
| 5.7                          | Novel Theory Developed                                | 159 |
| 5.8                          | Accomplishment of Research Objectives                 | 160 |

|                             |     |
|-----------------------------|-----|
| <b>REFERENCES</b>           | 161 |
| <b>LIST OF PUBLICATIONS</b> | 169 |

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## LIST OF TABLES

| NO.  |  | PAGE |
|------|--|------|
| 2.1  | Comparison of losses between metallic waveguides.                          | 13   |
| 2.2  | Physical and chemical properties of TOPAS material.                        | 22   |
| 2.3  | List of significant improvements in previous related researches.           | 58   |
| 3.1  | Cartesian coordinates (x, y) of air holes in triangular array.             | 66   |
| 3.2  | Cartesian coordinates (x, y) of air holes in hexagonal arrangement.        | 68   |
| 3.3  | Comparison of methods followed in different reported waveguides.           | 83   |
| 4.1  | Air hole parameters of the proposed design.                                | 87   |
| 4.2  | Mesh element property used in COMSOL.                                      | 91   |
| 4.3  | Comparison of EML with different previously reported waveguides.           | 102  |
| 4.4  | Comparison of dispersion properties of different reported waveguides.      | 108  |
| 4.5  | Parameters for 4 hexagonal cladding rings design.                          | 111  |
| 4.6  | Parameters for 5 hexagonal cladding rings design.                          | 124  |
| 4.7  | Comparison of number of elements for different core areas.                 | 140  |
| 4.8  | Comparison in ideal design parameters for different core areas.            | 141  |
| 4.9  | Comparison of index profile for single mode confinements.                  | 143  |
| 4.10 | Effect on EML for different core areas.                                    | 145  |
| 4.11 | Confinement loss at 1THz for different core area designs.                  | 146  |
| 4.12 | Effect on bending loss for different core area design.                     | 147  |
| 4.13 | Changes in power fraction at changed design parameters.                    | 150  |
| 4.14 | Near zero flat dispersion characteristics for different core area designs. | 153  |

## LIST OF FIGURES

| NO.  |  | PAGE |
|------|--|------|
| 1.1  | THz band in electromagnetic spectrum.                          | 1    |
| 1.2  | General scope of work of the research.                         | 8    |
| 2.1  | Honeycomb design by Neilsen et al. in 2011 (K. Nielsen, 2011). | 26   |
| 2.2  | Reported loss in (K. Nielsen, 2011).                           | 27   |
| 2.3  | Polymer MOF designed reported in (Ung, 2011).                  | 28   |
| 2.4  | Porous structure by Uthman et al. in 2012 (Uthman, 2012).      | 28   |
| 2.5  | Bending loss properties reported in (Uthman, 2012).            | 29   |
| 2.6  | Honeycomb fiber fabrication by Bao et al. (Hualong, 2012).     | 30   |
| 2.7  | Material loss & index profile reported in (Hualong, 2012).     | 30   |
| 2.8  | Porous fiber design by Chen et al. in 2013 (Na-na Chen, 2013). | 31   |
| 2.9  | Birefringence reported in (Na-na Chen, 2013).                  | 31   |
| 2.10 | Structure proposed by Kaijage et al. in 2013 (Kaijage, 2013).  | 33   |
| 2.11 | Effect of core diameter on material loss (Kaijage, 2013).      | 33   |
| 2.12 | Effect of porosity on material loss (Kaijage, 2013).           | 33   |
| 2.13 | Waveguide design by Jian et al. in 2013 (Liang, 2013).         | 34   |
| 2.14 | Reported confinement loss in (Liang, 2013).                    | 35   |
| 2.15 | Reported dispersion properties in (Liang, 2013).               | 35   |
| 2.16 | Triangular lattice reported by (Shaopeng, 2014).               | 36   |
| 2.17 | Effective refractive index reported by (Shaopeng, 2014).       | 37   |
| 2.18 | Reported birefringence by (Shaopeng, 2014).                    | 37   |
| 2.19 | Dispersion presented by (Shaopeng, 2014).                      | 37   |
| 2.20 | Reported loss by (Shaopeng, 2014).                             | 38   |

|      |   |    |
|------|---|----|
| 2.21 | Hybrid Porous PCF by Imran et al. in 2014 (Hasan, 2014).                | 39 |
| 2.22 | Investigation of EML reported by (Hasan, 2014).                         | 39 |
| 2.23 | Reported EML at optimum parameters (Hasan, 2014).                       | 40 |
| 2.24 | Dispersion reported by (Hasan, 2014).                                   | 40 |
| 2.25 | Octagonal lattice PCF proposed by (Rana, 2014).                         | 42 |
| 2.26 | EML response for different parameters by (Rana, 2014).                  | 42 |
| 2.27 | Core air hole EML & power fraction in (Rana, 2014).                     | 43 |
| 2.28 | Confinement loss of the proposed fiber in (Rana, 2014).                 | 43 |
| 2.29 | Spiral structure fiber designed by (R. Islam, 2015).                    | 44 |
| 2.30 | Effect of porosity on bending loss (R. Islam, 2015).                    | 44 |
| 2.31 | Reported bending loss vs. THz frequency in (R. Islam, 2015).            | 45 |
| 2.32 | Losses reported for different porosity in (R. Islam, 2015).             | 46 |
| 2.33 | EML & confinement loss at 1 THz reported in (R. Islam, 2015).           | 46 |
| 2.34 | Slotted core design proposed by (R. Islam, 2015).                       | 47 |
| 2.35 | Reported birefringence for different Dcore & porosity (R. Islam, 2015). | 48 |
| 2.36 | Birefringence for changing frequency reported in (R. Islam, 2015).      | 48 |
| 2.37 | Reported EMLs for different Dcore & porosity in (R. Islam, 2015).       | 49 |
| 2.38 | Reported confinement loss & EML in (R. Islam, 2015).                    | 49 |
| 2.39 | Fraction of power in air slots reported by (R. Islam, 2015).            | 50 |
| 2.40 | Dispersion properties reported by (R. Islam, 2015).                     | 51 |
| 2.41 | Rotated porous core design by (R. Islam, 2015).                         | 52 |
| 2.42 | EMLs for different Dcore & porosity in (R. Islam, 2015).                | 53 |
| 2.43 | Power fraction for different Dcore & porosity in (R. Islam, 2015).      | 54 |
| 2.44 | Confinement loss reported by (R. Islam, 2015).                          | 54 |
| 2.45 | Reported bending loss in (R. Islam, 2015).                              | 55 |

|      |   |    |
|------|---|----|
| 2.46 | Dispersion properties reported in (R. Islam, 2015).             | 55 |
| 3.1  | Flow chart of research methodology.                             | 63 |
| 3.2  | Novel design methodology using hybrid core.                     | 65 |
| 3.3  | Hexagonal cladding design for the proposed waveguide.           | 69 |
| 3.4  | PML boundary of porous fiber.                                   | 70 |
| 3.5  | Model builder in COMSOL Multiphysics 4.2.                       | 71 |
| 3.6  | Inserting design parameters in COMSOL software.                 | 72 |
| 3.7  | Designing circles in COMSOL Multiphysics.                       | 72 |
| 3.8  | Inserting material properties in COMSOL.                        | 73 |
| 3.9  | Inserting equations in COMSOL.                                  | 75 |
| 3.10 | Solution of equation in COMSOL.                                 | 75 |
| 3.11 | Mesh tab in COMSOL.   | 76 |
| 4.1  | Transverse cross section of the proposed porous core fiber.     | 86 |
| 4.2  | Air hole arrangement in cladding.                               | 89 |
| 4.3  | Air hole distribution in the core.                              | 90 |
| 4.4  | Normal mesh element structure of proposed design.               | 92 |
| 4.5  | Fine mesh element structure of proposed design.                 | 92 |
| 4.6  | Extremely fine mesh element structure of proposed design.       | 92 |
| 4.7  | Eigenvalue solver used in COMSOL.                               | 93 |
| 4.8  | EML for different Dcore and porosity at 1THz frequency.         | 94 |
| 4.9  | Effect of core diameter on EML of proposed fiber.               | 95 |
| 4.10 | Effect of porosity on EML of proposed fiber.                    | 96 |
| 4.11 | Fundamental mode field distribution at 1THz for x polarization. | 97 |
| 4.12 | Fundamental mode field distribution at 1THz for y polarization. | 97 |
| 4.13 | Effective refractive index of proposed design.                  | 99 |

|      |   |     |
|------|---|-----|
| 4.14 | EML response as a function of frequency at optimum parameters.    | 100 |
| 4.15 | Comparison of EML characteristics.                                | 101 |
| 4.16 | Confinement loss for optimum design parameters.                   | 103 |
| 4.17 | Bending loss for optimum design parameters at 1cm bending radii.  | 104 |
| 4.18 | Fraction of power at optimum design parameter.                    | 105 |
| 4.19 | Dispersion characteristics at optimum design parameters.          | 106 |
| 4.20 | Comparison of dispersion properties.                              | 108 |
| 4.21 | Air hole distribution with 4 hexagonal cladding rings.            | 111 |
| 4.22 | Mesh elements used by COMSOL to present the structure.            | 112 |
| 4.23 | Eigenvalue solver used for the design in COMSOL.                  | 113 |
| 4.24 | EML response for different core diameter & porosity.              | 114 |
| 4.25 | Confinement loss at different core diameter & porosity.           | 114 |
| 4.26 | Bending loss at different core diameter & porosity.               | 115 |
| 4.27 | Confinement loss at 47% porosity at 1THz frequency.               | 115 |
| 4.28 | Confinement loss at 47% porosity at 1THz frequency.               | 116 |
| 4.29 | Fundamental mode field distribution of x polarization.            | 117 |
| 4.30 | Fundamental mode field distribution of y polarization.            | 117 |
| 4.31 | Refractive index profiles at 8.38% core area design.              | 119 |
| 4.32 | EML at ideal parameters for 8.38% core area design.               | 119 |
| 4.33 | Confinement loss for 8.38% core area design at ideal parameters.  | 120 |
| 4.34 | Bending loss for 8.38% core area design at ideal parameters.      | 121 |
| 4.35 | Fraction of power for 8.38% core area design at ideal parameters. | 122 |
| 4.36 | Dispersion for 8.38% core area design at ideal parameters.        | 123 |
| 4.37 | Air hole distribution with 5 hexagonal cladding rings.            | 125 |
| 4.38 | Mesh elements used by COMSOL to present the structure.            | 126 |

|      |   |     |
|------|---|-----|
| 4.39 | Eigenvalue solver used for the design in COMSOL.                    | 127 |
| 4.40 | EML response for different core diameter & porosity.                | 128 |
| 4.41 | Confinement loss at 60% porosity for different core diameters.      | 128 |
| 4.42 | Bending loss at 60% porosity for different core diameters.          | 129 |
| 4.43 | EML for 60% porosity at 1THz frequency.                             | 130 |
| 4.44 | Fundamental mode field distribution of x polarization.              | 131 |
| 4.45 | Fundamental mode field distribution of y polarization.              | 131 |
| 4.46 | Refractive index profiles at 2.70% core area design.                | 132 |
| 4.47 | EML for 2.70% core area design at ideal parameters.                 | 133 |
| 4.48 | Confinement loss for 2.70% core area design at ideal parameters.    | 134 |
| 4.49 | Bending loss for 2.70% core area design at ideal parameters.        | 135 |
| 4.50 | Fraction of power for 2.70% core area design.                       | 136 |
| 4.51 | Dispersion for 2.70% core area design at ideal parameters.          | 137 |
| 4.52 | Air hole arrangement at core area of (a) OCD, (b) RCD-A, (c) RCD-B. | 139 |
| 4.53 | Light confinements at core area of (a) OCD, (b) RCD-A, (c) RCD-B.   | 140 |
| 4.54 | Comparison of effective refractive index.                           | 143 |
| 4.55 | Effects on EML for different core areas.                            | 144 |
| 4.56 | Changes in confinement loss for different core areas.               | 146 |
| 4.57 | Difference in bending loss for changing core area.                  | 148 |
| 4.58 | Comparison of power fraction in core air holes.                     | 148 |
| 4.59 | Comparison of power fraction in cladding air holes.                 | 149 |
| 4.60 | Comparison of power fraction in the material (TOPAS).               | 150 |
| 4.61 | Dispersion properties for different core area designs.              | 151 |
| 4.62 | Near zero flat dispersion characteristics for different core areas. | 152 |

## LIST OF ABBREVIATIONS

|       |                              |
|-------|------------------------------|
| THz   | Terahertz                    |
| PCF   | Photonic Crystal Fiber       |
| EML   | Effective Material Loss      |
| FEM   | Finite Element Method        |
| FEA   | Finite Element Analysis      |
| PML   | Perfectly Matched Layer      |
| PEC   | Perfect Electric Conductor   |
| TIR   | Total Inter Reflection       |
| TE    | Transverse Electric          |
| HB    | High Birefringence           |
| MOF   | Microstructure Optical Fiber |
| OCD   | Optimum Core Design          |
| RCD-A | Reduced Core Design – A      |
| RCD-B | Reduced Core Design – B      |

## LIST OF SYMBOLS

|                             |  |
|-----------------------------|--|
| $[s]$                       | PML matrix   |
| $[s]^{-1}$                  | Inverse $[s]^{-1}$                                   |
| $k$                         | Wave number in the vacuum                            |
| $n_{\text{eff}}$            | Effective refractive index                           |
| $\beta$                     | Modal propagation constant                           |
| $k_0$                       | Free-space wave number                               |
| $\lambda$                   | Wave length  |
| $\alpha_{\text{eff}}$       | Effective Material Loss (EML) ( $\text{cm}^{-1}$ )   |
| $\alpha_{\text{mo}}$        | Loss of fundamental mode                             |
| $\alpha_{\text{mat}}$       | Loss from material absorption in the fiber           |
| $\epsilon_0$                | Permittivity of free space                           |
| $\mu_0$                     | Permeability of free space                           |
| $S_z$                       | Pointing vector of $z$ - component                   |
| $\alpha_{\text{CL}}$        | Confinement loss ( $\text{cm}^{-1}$ )                |
| $\text{Im}(n_{\text{eff}})$ | Imaginary part of the refractive index               |
| $n_{\text{eq}}(x,y)$        | Modified equivalent index profile                    |
| $n(x,y)$                    | Original refractive index profile                    |
| $x$                         | Distance from bending point (cm)                     |
| $R$                         | Bending radii (cm)                                   |
| $\beta_2$                   | Second order term in the Taylor expansion of $\beta$ |
| $c$                         | Velocity of light                                    |
| $D_{\text{core}}$           | Core diameter ( $\mu\text{m}$ )                      |

## **Jalur Lebar Penyebaran Rata menggunakan Teras Fiber Krystal Fotonik berliang untuk Pemandu Gelombang THz yang rendah kerugian**

### **ABSTRAK**

Secara kasar, radiasi terahertz (THz) ditakrifkan diantara frekuensi band 0.1 ke 10 THz. Ia merapatkan jurang antara gelombang mikro dan panjang gelombang optik dan telah menarik minat pengkaji kerana berpotensi untuk digunakan dalam spektroskopi, pengimejan bukan invasif, penderian bioperubatan, astronomi, keselamatan kawasan sensitif seperti memantau ubat-ubatan, bahan letupan atau senjata dengan cara yang bukan pemusnah, penghibridan DNA dan komunikasi. Sebahagian besar daripada sistem THz sedia ada bersaiz besar dan bergantung kepada penyebaran di ruang terbuka sahaja kerana kurangnya pemandu gelombang yang mampu membuat penghantaran yang rendah kerugiannya dalam spektrum THz. Justeru, kajian terhadap pemandu gelombang THz yang berjaya yang memiliki kadar kerugian rendah, nilai komersil yang baik, berkesan dan fleksibel merupakan sesuatu yang tidak dapat dielakkan. Dalam kajian ini, kemajuan dan ciri-ciri sebuah teras dielektrik berliang dikaji untuk mendapatkan pemandu gelombang THz yang sesuai untuk aplikasi komunikasi. Sejenis reka bentuk teras fiber berliang hibrid yang novel telah dicipta menggunakan bahan TOPAS. Ciri-ciri perambatan bagi teras fiber yang berbeza keliangan dan diameter telah dikaji dengan peratusan luas teras yang berbeza. Kesan memutarakan susunan segi tiga lubang udara di dalam kawasan teras hibrid keatas perambatan telah dikaji bagi reka bentuk yang dicadang. Hasil simulasi menunjukkan bahawa EML yang rata-ratanya rendah bernilai  $0.0398 \pm 0.000416 \text{ cm}^{-1}$  terhasil daripada terahertz (THz) antara 1.5 ke 5 dengan pembendung yang boleh diabaikan dan kerugian lipatan sebanyak 17.89% daripada luas teras jumlah fiber. Selain dari itu pemandu gelombang yang di hasilkan juga menghasilkan penyebaran rata pada  $0.4 \pm 0.042 \text{ ps/THz/cm}$  pada kekerapan 1.25 ke 5.0 THz. Reka bentuk baru yang dilaporkan dan hasil yang berinovasi yang mempunyai ciri khas telah menunjukkan bahawa fiber teras berliang yang dicadangkan memiliki potensi yang perlu diberi perhatian untuk aplikasi komunikasi.

## **Broadband Dispersion Flattened Porous Core Photonic Crystal Fiber for Low Loss THz Wave Guiding**

### **ABSTRACT**

Terahertz (THz) radiation can be loosely defined in the frequency domain from 0.1 to 10 THz bands. It bridges the gap between microwave and optical wavelength and has already confined the researcher interest due its potential applications in spectroscopy, non-invasive imaging, biomedical sensing, astronomy, security sensitive areas such as monitoring drugs, explosives or weapons in a non-destructive manner, hybridization of DNA and communications. A large number of the existing THz system are bulky and rely on free space propagation due to the lack of low-loss transmission waveguides in the THz spectrum. Therefore, the investigation of low-loss, commercially feasible, efficient and flexible waveguides for the exultant execution of THz scheme becomes incapable of being disregarded. In this research, performance and properties of a porous core dielectric fiber has been studied to find a suitable THz waveguide for communication applications. A novel type of hybrid core porous fiber design has been developed using TOPAS material. Propagation characteristics for different fiber core porosity and core diameter have been studied with different percentages of core areas. The effects of rotating the triangular air hole arrangements in the hybrid core region on propagation have been studied for the proposed design. Simulation results show a flat low EML of  $0.0398 \pm 0.000416 \text{ cm}^{-1}$  from 1.5 to 5 terahertz (THz) range with negligible confinement and bending loss with 17.89% core area of the total fiber. Also the reported waveguide exhibits a near zero flat dispersion at  $0.4 \pm 0.042 \text{ ps/THz/cm}$  in the frequency range from 1.25 to 5.0 THz. The reported novel design and innovative results with special features have indicated the noteworthy potentiality of the proposed porous core fiber as a reliable THz waveguide for communication applications.

# CHAPTER 1

## INTRODUCTION

### 1.1 Introduction

Terahertz (THz) frequency regime can be generally defined in the frequency domain from 0.1 to 10 THz in the electromagnetic spectrum (Lee, 2009; Xi-Cheng Zhang, 2010). This particular band is often referred to as “THz gap” due to its historical difficulty to exploit for practical applications. THz frequency range is lying between electrical and optical frequencies, each of which utilizes very different hardware. As a result the development of affordable technologies for THz regime has been slower than other frequency bands. Fig. 1.1 explains the position of THz regime in the electromagnetic spectrum.

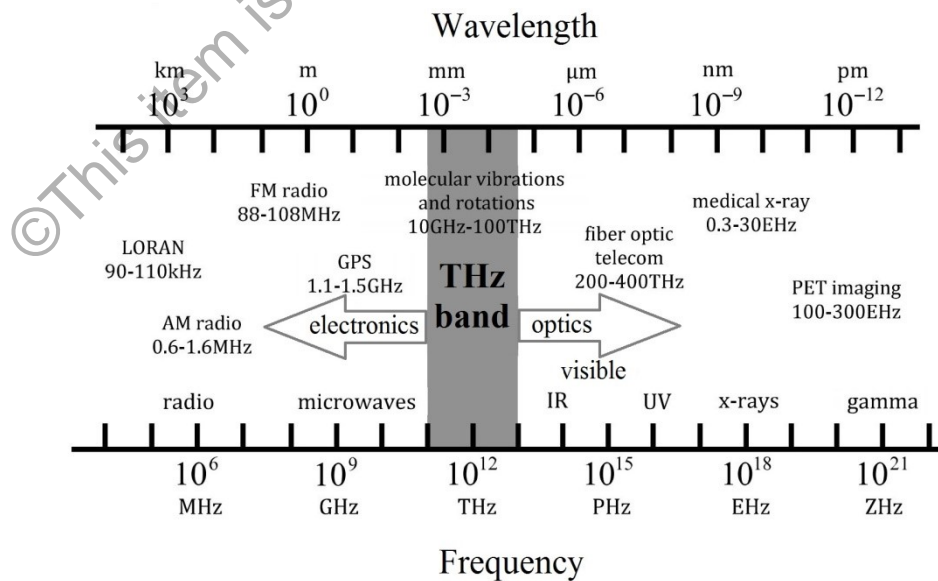


Figure 1.1: THz band in electromagnetic spectrum.

Researchers' interests for THz regime come from the vast potential applications of this frequency domain in spectroscopy (Xi-Cheng Zhang, 2010), non-invasive imaging (Q. Chen, Z.P. Jiang, G.X. Xu, X.C. Zhang, 2000), biomedical sensing (He, 2008), astronomy (Ho, 2008), security sensitive areas such as monitoring drugs (Strachan, 2005), explosives or weapons in a non-destructive manner (Cook, 2005), hybridization of DNA (M. Nagel, Bolivar, P. H., Brucherseifer, M., Kurz, H., Bosserhoff, A., & Büttner, R., 2002) and communications (Hasan, 2014). However, adapting the technologies for THz regime has been proven difficult due to the absent of a suitable transmitting medium. At present, the existing THz systems are bulky and mostly depend on propagation via free space or air. Thus, researchers are focusing their interest on finding a low loss waveguide for the terahertz frequency regime.

Waveguides are physical structures that are used to propagate waves; such as, electromagnetic waves or sound waves etc. In case of electromagnetic waves this is an alternative to free space propagation. Waveguides are made from different materials, like metal or dielectric materials and they may come in different shapes and sizes (S. Atakaramians, Shahraam Afshar, Tanya M Monro, Derek Abbott, 2013). The primary application of a waveguide is to propagate a signal with minimum power loss. The host material and structure of a waveguide can be organized to meet different applications.

Number of investigations has been reported in the past years to develop a proper waveguide for different applications using THz frequency radiation. In this thesis, porous core photonic crystal fibers are studied to investigate its performance as a suitable waveguide for THz regime in communication applications.

## 1.2 Research Background

Numbers of waveguides for THz regime have been proposed in the past few years; such as, metallic wires (M. Wächter, 2007), dielectric metal-coated tubes (Bowden, 2007), all-dielectric sub-wavelength polymer fibers (A. Hassani, 2008), dielectric sub-wavelength waveguide (G. Emiliyanov, J. Jensen, O. Bang, P. Hoiby, L. Pedersen, E. Kjær, and L. Lindvold, 2007), solid dielectric core with a sub wavelength hole in middle (J. S. Melinger, 2009), porous structure of sub wavelength air hole (Alexandre Dupuis, 2010), Bragg fibers (C. Markos, 2013) etc. However, most of the proposed waveguides in the past are unable to fulfil the low loss transmission medium requirement for THz regime. For example, metal waveguides have unstable guidance, high bending loss and low coupling efficiency (Wang Kanglin, 2004). In case of dielectric rod waveguides, absorption loss by surrounding air, bending and confinement losses are vital drawbacks (H. W. Chen, 2009). In the solid core waveguides, THz propagation suffers from a large material absorption loss (J. S. Melinger, 2009). Also in other proposed wave guides material absorption loss is an issue (Y. Y. Wang, 2011). For these shortcomings, a considerable portion of THz system depends on free space propagation due to the absence of a good low loss waveguide in the THz spectrum.

In order to compress the propagation loss further, scientists are considering photonic crystal fibers (PCFs) (Kaijage Shubi, 2009), hollow-core fibers (Jessienta Anthony, 2011) and polymer porous fibers (Liang, 2013) as THz waveguides (S. Atakaramians, Shahraam Afshar, Tanya M Monroe, Derek Abbott, 2013). The sub-wavelength polymer porous fiber has shown better results in THz transmission for its advantages of lower material absorption loss (Uthman, 2012), high birefringence for

sensing applications (Na-na Chen, Jian Liang, and Li-yong Ren, 2013) and tuneable dispersion for communication applications (Rana, 2014) etc.

To date many researchers have reported low loss porous core PCFs with remarkable guiding properties regarding EML, birefringence and dispersion. Liang *et al.* (Liang, 2013) proposed a porous core fiber with a material absorption loss of  $0.432 \text{ cm}^{-1}$  for communication applications in 2013. Their proposed waveguide resulted in a flat dispersion range of 0.17 THz with an absolute dispersion variation that is less than 2.5 (ps/THz/cm).

In 2014, Rana *et al.* (Rana, 2014) proposed a porous core fiber with material absorption loss of  $0.05 \text{ cm}^{-1}$  at 1 THz operating frequency, however the design showed no dispersion flattened properties. In 2014, Imran *et al.* (Hasan, 2014) proposed an octagonal porous core with an absorption loss of  $0.056 \text{ cm}^{-1}$  and near zero flat dispersion of  $\pm 0.18 \text{ ps/THz/cm}$  with dispersion range of 0.8 THz.

In 2015 Islam *et al.* proposed a THz waveguide with an absorption loss of  $0.07 \text{ cm}^{-1}$  with zero flat dispersion of  $\pm 0.5 \text{ ps/THz/cm}$  with a range of 0.3 THz (R. Islam, S. Habib, GKM. Hasanuzzaman, R. Ahmad, S. Rana and S.F. Kaijage, 2015). Same year, Islam *et al.* (R. Islam, Hasanuzzaman GKM, Habib Selim, Rana Sohel, Khan MAG, 2015) proposed another porous fiber design using hexagonal structure. They reported a low material absorption loss of  $0.066 \text{ cm}^{-1}$  at the operating frequency of 1 THz. A near zero flat dispersion of  $\pm 0.12 \text{ ps/THz/cm}$  at  $1.06 \text{ ps/THz/cm}$  in the frequency range of 0.5–1.08 THz was reported in that design. However, none of the previous porous core waveguides showed a wide frequency range of flat material absorption loss with near zero flat dispersion characteristics.

### 1.3 Problem Statement

Material absorption loss is a vital loss mechanism in porous core waveguides for THz band. It occurs in fibers for the presence of imperfections in the structure of atoms in the fiber host material. The material loss differs from one material to another due to some basic intrinsic and extrinsic properties that material. This loss is better known as Effective Material Loss (EML) for porous core fibers (Hasan, 2014; R. Islam, Hasanuzzaman GKM, Habib Selim, Rana Sohel, Khan MAG, 2015). Porous core fibers are single material photonic crystal fiber having higher number of air holes in the core region resulting in high porosity. In recent years, some reported porous core fibers showed low EML at THz frequency (R. Islam, Hasanuzzaman GKM, Habib Selim, Rana Sohel, Khan MAG, 2015; Liang, 2013; Rana, 2014). However, the proposed waveguides show a low EML only at a particular frequency (such as, 1 THz) rather than having a frequency range of low EML response in THz regime. To be considered as a useful waveguide for THz regime, porous fibers should deliver a large frequency range of low and flat EML response. Previous reports show that a higher porosity on the core region results in a low value of EML. This higher porosity can be obtained by designing the porous core with higher number of larger sized air holes. None of the previous designs show flat EML response in the THz regime. Thus the fundamental of achieving a flat EML in THz band is still an untouched territory in this research topic.

A near zero flat dispersion characteristic is needed to be present in a porous core waveguide for utilization in communication applications at THz frequencies. The long range of flatness in dispersion as a function of frequency and lower value of absolute dispersion coefficient are the two primary criteria for near zero flat dispersion. Some porous core waveguides showed near zero flatness in dispersion previously (Hasan,