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

by

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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_{eff}	Effective refractive index
β	Modal propagation constant
k_0	Free-space wave number
λ	Wave length
α_{eff}	Effective Material Loss (EML) (cm^{-1})
α_{mo}	Loss of fundamental mode
α_{mat}	Loss from material absorption in the fiber
ε_0	Permittivity of free space
μ_0	Permeability of free space
S_z	Pointing vector of z - component
α_{CL}	Confinement loss (cm^{-1})
$\mathrm{Im}(n_{\mathrm{eff}})$	Imaginary part of the refractive index
$n_{\mathrm{eq}}(x,y)$	Modified equivalent index profile
$n(x,y)$	Original refractive index profile
x	Distance from bending point (cm)
R	Bending radii (cm)
β_2	Second order term in the Taylor expansion of β
c	Velocity of light
Dcore	Core diameter (μm)

Jalur Lebar Penyebaran Rat a menggunakan Teras Fiber Krystal Fotonik berliang untuk Pemandu Gelombang THz yang rendah kerugian

ABSTRAK

Secara kasar, radiasi teraheartz (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 memutarkan susunan segi tiga lubang udara di dalam kawasan teras hibrid keatas perambatan telah dikaji bagi reka bentuk yang dicadang. Hasil simulasi menunjukan bahawa EML yang rata-ratanya rendah bernilai 0.0398±0.000416 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±0.042 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 menunjukan 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±0.000416 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±0.042 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.

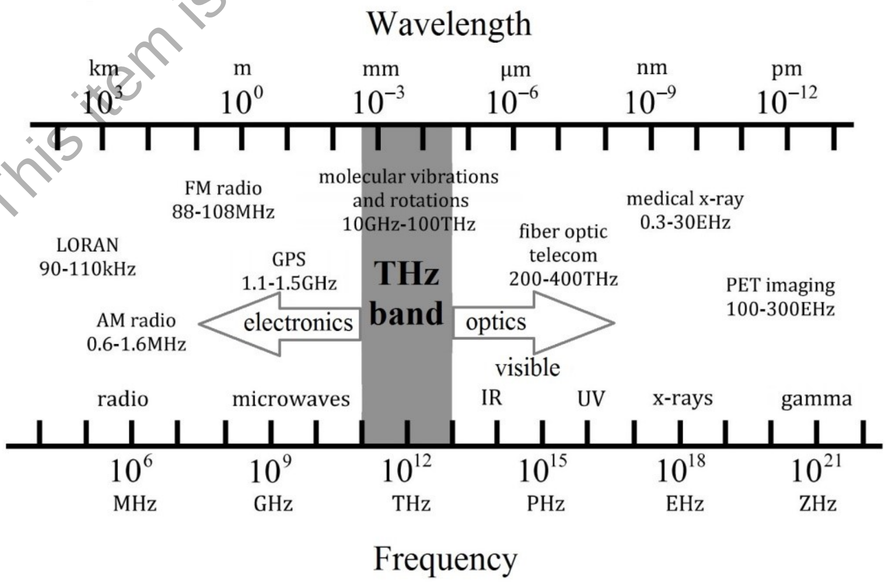

Figure 1.1: THz band in electromagnetic spectrum.

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 Monro, 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 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 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 cm^{-1} and near zero flat dispersion of ±0.18 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 cm^{-1} with zero flat dispersion of ±0.5 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 cm^{-1} at the operating frequency of 1 THz. A near zero flat dispersion of ± 0.12 ps/THz/cm at 1.06 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,