

# UNIVERSITI PUTRA MALAYSIA

# DESIGN AND DEVELOPMENT OF VARIABLE FIBER OPTIC COUPLER

MARSYITA HANAFI.

FK 2006 3



# DESIGN AND DEVELOPMENT OF VARIABLE FIBER OPTIC COUPLER

**MARSYITA HANAFI** 

# MASTER OF SCIENCE UNIVERSITI PUTRA MALAYSIA

2006



# DESIGN AND DEVELOPMENT OF VARIABLE FIBER OPTIC COUPLER

By

# MARSYITA BINTI HANAFI

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

January 2006



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

# **DESIGN AND DEVELOPMENT OF VARIABLE FIBER OPTIC COUPLER**

By

## **MARSYITA HANAFI**

#### January 2006

## Chairman: Associate Professor Mohd Khazani Abdullah, PhD

## Faculty: Engineering

This thesis presents the research works on design, development and analysis of variable fiber optic coupler.

The fiber couplers are devices that distribute light from a main fiber into one or more branches of fibers which can be used as a power divider, wavelength-division multiplexer (WDM) and optical switches. These couplers are important in all fiber optic networks as they are used in long haul, metro, distribution and access fiber networks. With the widely increasing deployment of metropolitan area network, fiberto-the-home (FTTH) and cable TV networks, the market potential for the fiber couplers is becoming larger.

However, most of the fiber couplers can only provide a fixed optical coupling ratio which is unable to provide flexibility, reliability and scalability. The evolution of the telecommunications networks has created an increasing demand for the variable fiber



couplers, but there are some limitations of the existing variable fiber couplers such as unstable, small tuning range of coupling ratio, high in loss and costly. Hence, this gives rise to the need for searching new design of developing better performance variable fiber couplers. The new design utilize a fix coupling ratio Fused Biconical Tapered (FBT) coupler that is involved low loss coupling process and low in cost. This coupler is known as a Variable Fiber Optic Coupler (VFOC).

There are two approaches used in this thesis that are simulation and experimentation. The simulation is important in designing the VFOCs, as through the simulation process, the characteristic of the design VFOCs can be determined. The successful simulation is then realized through the experimentation, which is included the fabrication of the VFOCs. However, the results obtained from the experiments are slightly different from the simulation results. These are due to the losses in the experiments and the ideal environment in the simulation.

In the experiment, the variable coupling ratio is achieved by applying deflection to the fabricated FBT couplers. The dependency of the variable coupling ratio on the deflection is elaborated. It is found that in the range of 0.8 mm deflection, the coupling ratio can be varied from 11% to 92% with the excess loss less than 0.1 dB.



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

# **REKABENTUK PENGGANDING GENTIAN OPTIK BOLEH UBAH**

Oleh

# **MARSYITA HANAFI**

# Januari 2006

# Pengerusi: Profesor Madya Mohd Khazani Abdullah, PhD

# Fakulti: Kejuruteraan

Tesis ini mempamerkan penyelidikan pada rekabentuk dan analisis bagi pengganding gentian optik boleh ubah.

Pengganding gentian adalah peranti yang mengagihkan cahaya daripada gentian utama kepada satu atau lebih cabang gentian yang boleh digunakan sebagai pembahagi kuasa, pemultipleks pembahagian gelombang (WDM) dan suis optik. Pengganding adalah penting dalam semua rangkaian gentian optik kerana mereka digunakan di dalam rangkaian gentian berlanjutan, metro, pengagihan dan capaian. Dengan peningkatan penggunaan rangkaian kawasan metropolitan, gentian ke rumah (FTTH) dan rangkaian kabel TV, potensi pasaran untuk pengganding gentian semakin berkembang.

Sungguhpun begitu, kebanyakkan pengganding gentian hanya boleh memberikan gandingan nisbah optik yang tetap, yang tidak berupaya memberikan kebolehlenturan,



kebolehpercayaan dan kebolehskalaan. Evolusi rangkaian telekomunikasi telah mewujudkan peningkatan dalam permintaan terhadap pengganding gentian pemboleh ubah, tetapi terdapat beberapa kelemahan pada pengganding gentian pemboleh ubah yang sedia ada seperti tidak stabil, julat penalaan gandingan nisbah yang kecil, kehilangan yang tinggi dan mahal. Oleh yang demikian, ini meningkatkan keinginan untuk mencari reka bentuk baru bagi penghasilan pengganding gentian pemboleh ubah yang berprestasi lebih baik. Rekabentuk baru menggunakan pengganding FBT dengan nisbah gandingan tetap yang melibatkan proses gandingan kehilangan rendah dan murah. Pengganding ini dikenali sebagai pengganding gentian optik boleh ubah (VFOC).

Terdapat dua pendekatan yang digunakan di dalam tesis ini iaitu simulasi dan pengujikajian. Simulasi adalah opsyen mutlak dalam merekabentuk semua VFOC, di mana melalui proses simulasi, ciri-ciri bagi rekabentuk semua VFOC boleh ditentukan. Kejayaan simulasi boleh direalisasikan melalui pengujikajian, iaitu termasuk pembikinan semua VFOC. Sungguhpun begitu, keputusan yang diperolehi daripada pengujikajian adalah berbeza sedikit daripada keputusan simulasi. Ini adalah disebabkan kewujudan kehilangan dalam pengujikajian, dan persekitaran unggul di dalam simulasi.

Berdasarkan keputusan pengujikajian, keboleh lenturan nisbah gandingan bagi semua VFOC terbikin telah ditunjukkan. Nisbah gandingan pemboleh ubah diperolehi dengan menggenakan pesongan kepada pengganding FBT terbikin. Kebergantungan



nisbah gandingan pemboleh ubah ke atas pesongan dihuraikan. Didapati bahawa di dalam julat pesongan 0.8 mm, nisbah gandingan boleh diubah daipada 11% kepada 92% bersama kehilangan lebihan kurang dari 0.1 dB.



## **ACKNOWLEDGEMENTS**

First of all, I would like to express my greatest attitude to ALLAH the almighty, for his help and support during the course of life and moment of truth. Alhamdullilah.

I would like to sincerely thank my supervisor, Associate Professor Dr Mohamad Khazani Abdullah for his continuous support, encouragement and endless patience towards completing the research. Special thanks to my thesis supervisory committee Prof. Dr. Sahbudin Shaari and Puan Siti Barirah Ahmad Anas.

I would also like to thank Mr Ahmad Zaki Shaari for allowing me to use the fabrication facilities and also for his cooperation and guidance in helping me completing the experiment works. Working with him is a good experience that could never be forgotten.

Special appreciation to my beloved husband and daughter, Muhd Anwar Ramli and Afrina Batrisyia for their continual support and encouragement in whatever I do. Last but not least, special thank to my beloved parent, Sofiah Abdullah and Hanafi Abdullah and the rest of the family. Thank you.



# **TABLE OF CONTENT**

ABSTRACT	ii
ABSTRAK	iv
ACKNOWLEDGEMENTS	vii
APPROVAL	viii
DECLARATION	х
LIST OF TABLES	xiii
LIST OF FIGURES	xiv
LIST OF ABBREVIATIONS	xix

# CHAPTER

1	INTF	RODUCTION	
	1.1	Background	1
	1.2	Problem Statement	2
	1.3	Objectives	4
	1.4	Scope of Work	4
	1.5	Thesis Overviews	5
2 TH	THE	ORY AND PRINCIPLE	
	2.1	Introduction	7
	2.2	Basic Concept of Optical Fiber Coupler	7
	2.3	Types of Optical Fiber Couplers	8
		2.3.1 Three and Four Port Couplers	9
		2.3.2 Star Coupler	14
		2.3.3 Wavelength Division Multiplexing (WDM) Device	16
		2.3.4 Variable Fiber Optic Coupler (VFOC)	17
	2.4	Principle Operation of the Fused Biconical Taper Coupler	18
	2.5	Couple-Mode Theory	19
	2.6	Coupling in the VFOC	23
3	DESI	GN AND SIMULATION RESULTS	
	3.1	Introduction	27
	3.2	Overview of BPM_CAD	27
		3.2.1 BPM 3D for Fibers	28
	3.3	VFOC: Parameters Under Study	32
		3.3.1 Design Parameters	32
		3.3.2 Performance Parameters	34
	3.4	Simulation Results of the Design VFOCs	37
		3.4.1 Selected Design Models	37
		3.4.2 Model I Simulation Results	39
		3.4.3 Model II Simulation Results	44
	3.5	Conclusion	59



4	FAB	RICATION METHODS	
	4.1	Introduction	61
	4.2	Description of Equipment Used In Fabrication	61
	4.3	Fabrication Method	64
		4.3.1 Parameters Setting	64
		4.3.2 Fiber Coating Removal and Placement	65
		4.3.3 Fiber Twisting	66
		4.3.4 Fusion and Elongation	67
		4.3.5 Packaging	68
	4.4	Coupling Ratio Variation Method	70
5	RES	ULTS AND ANALYSIS	
	5.1	Introduction	71
	5.2	The Effect of the Coupling Length on the Coupling Ratio	72
	5.3	The Performance of the VFOCs	74
		5.3.1 The Effect of Bending on the Coupling Ratio	75
		5.3.2 The Effect of Bending on the Excess Loss	83
		5.3.3 The Effect of Bending on the Insertion Loss	88
		5.3.4 The Effect of Bending on the Directivity	94
	5.4	Conclusion	99
6	CON	CLUSION AND FUTURE WORKS	
U U	61	Conclusion	100
	6.2	Future Works	100
	0.2		101
REF	ERENG	CES	102
APP	ENDIX	ES	106
BIO	BIODATA OF THE AUTHOR		126



# LIST OF TABLES

Table		Page
A.1	Data of the deflections at the corresponding bending angles.	108
B.1	Data of the VFOC with initial coupling ratio of 10:90 and at 1550nm	110
B.2	Data of the VFOC with initial coupling ratio of 20:80 and at 1550nm	110
B.3	Data of the VFOC with initial coupling ratio of 30:70 and at 1550nm	111
B.4	Data of the VFOC with initial coupling ratio of 40:60 and at 1550nm	111
B.5	Data of the VFOC with initial coupling ratio of 50:50 and at 1550nm	112
B.6	Data of the VFOC with initial coupling ratio of 50:50 and at 1310nm	112
B.7	Data of the VFOC with initial coupling ratio of 30:70 and at 1310nm	112
B.8	Data of the VFOC with initial coupling ratio of 10:90 and at 1310nm	113
C.1	Data of the VFOC with initial coupling ratio of 10:90 and at 1550nm	122
C.2	Data of the VFOC with initial coupling ratio of 20:80 and at 1550nm	122
C.3	Data of the VFOC with initial coupling ratio of 50:50 and at 1550nm	123



# LIST OF FIGURES

Figure		Page
2.1	Classification of Optical Fiber Coupler.	8
2.2	Three-Port Couplers.	9
2.3	A Four-Port Coupler.	10
2.4	Three Port-Fiber Coupler using Semitransparent Mirror Method.	11
2.5	Polished Directional Coupler.	12
2.6	Fused Biconical Tapered Directional Coupler.	14
2.7	Star Coupler.	15
2.8	8x8 Star Coupler form by cascading 12 four port couplers (ladder coupler).	15
2.9	Wavelength-division multiplexing (WDM) configuration.	16
2.10	Fused Biconical Taper Coupler.	19
2.11	Schematic Block Diagram of the VFOC.	24
2.12	Diagram of the FBT coupler that is used in the VFOC.	24
2.13	Top View of the Bent Coupler.	25
3.1	BPM3D Layout Designer: The Shaded Structures are the Fiber Optics in Top View.	29
3.2	Main Characteristics of the BPM 3DF Layout.	30
3.3	Simulation Result from BPM CAD.	32
3.4	Structure of the FBT Coupler.	35
3.5	Model I Represents Cladding Guidance Region.	38
3.6	Model II Represents the Down-Taper Region, the Taper-Waist Region and the Up-Taper Region.	39



3.7	Mode regions of the fiber for the core guidance and cladding guidance.	40
3.8	Propagation Field along the Coupling Length at 1550 nm.	41
3.9	Propagation Field along the Coupling Length at 1310 nm.	42
3.10	Power Distribution in Model 1.	43
3.11	Propagation Field along the Designed Coupler at 1° Bending Angle and at 1550 nm.	45
3.12	Propagation Field along the Designed Coupler at 2° Bending Angle and at 1550 nm.	46
3.13	Propagation Field along the Designed Coupler at 3° Bending Angle and at 1550 nm.	47
3.14	The Variation of the Coupling Ratio with the Bending Angle at 1550 nm Wavelength.	48
3.15	Propagation Field along the Designed Coupler at 1° Bending Angle and at 1310 nm.	49
3.16	Propagation Field along the Designed Coupler at 3° Bending Angle at 1310 nm.	50
3.17	The Variation of the Coupling Ratio with the Bending Angle at 1310 nm Wavelength.	50
3.18	Propagation Field along the 12 mm Coupling Length at 1° Bending Angle.	53
3.19	Propagation Field along the 12 mm Coupling Length at 5° Bending Angle.	54
3.20	The Variation of Coupling Ratio with the Coupling Length at 1° Bending Angle and at 1310 nm.	55
3.21	The Variation of Coupling Ratio with the Coupling Length at 5° Bending Angle and at 1310 nm.	55
3.22	Propagation Field along the Designed Coupler at 3.5 $\mu$ m Coupling Gap.	57



3.23	Propagation Field along the Designed Coupler at 8.5 μm Coupling Gap.	58
3.24	The variation of the coupling ratio with the Coupling gap at $1^{\circ}$ bending angle.	58
4.1	GYCW-4 System.	62
4.2	Front Open View of GYCW-4 Workstation.	62
4.3	Parameter Screen Setting.	65
4.4	Fibers Position on the Fiber Holders.	66
4.5	A structure of a pair twisted fibers.	67
4.6	Real-Time Panel Display.	68
4.7	A picture of fused coupler that is glued to a quartz tube.	69
4.8	A picture of fused coupler that is covered with a heat shrink tube.	69
4.9	A picture of VFOC.	70
5.1	The Variation of the Coupling Ratios with the Coupling Lengths	73
5.2	Real-Time Panel Display with Approximately 50% Coupling Ratio	75
5.3	Real-Time Panel Display with Approximately 40% Coupling Ratio	76
5.4	Real-Time Panel Display with Approximately 30% Coupling Ratio	77
5.5	The Variation of the Coupling Ratio with the Deflection at Different Initial Coupling Ratio Single-Mode VFOCS and at 1550 nm.	78
5.6	The Variation of the Coupling Ratio with the Deflection at Different Initial Coupling Ratio Multimode VFOCS and at 1550 nm.	80
5.7	The Variation of the Coupling Ratio with the Deflection at Different Initial Coupling Ratio Single-Mode VFOCs and at 1310 nm.	82
5.8	The Variation of the Excess Loss with the Deflection at Different	



	Initial Coupling Ratio Single-Mode VFOCs and at 1550 nm.	84
5.9	The Variation of the Excess Loss with the Deflection at Different Initial Coupling Ratio Multimode VFOCs and at 1550 nm.	85
5.10	The Variation of the Excess Loss with the Deflection at Different Initial Coupling Ratio, Single-Mode VFOCs and at 1310 nm.	87
5.11	The Variation of the Insertion Loss with the Deflection at Different Initial Coupling Ratio, Single-Mode VFOCs and at 1550 nm.	89
5.12	The Variation of the Theoretical Insertion Loss with the Deflection at Different Initial Coupling Ratio.	90
5.13	The Variation of the Insertion Loss with the Deflection at Different Initial Coupling Ratio, Multimode VFOCs and at 1550 nm.	91
5.14	The Variation of the Theoretical Insertion Loss with the Deflection at Different Initial Coupling Ratio.	92
5.15	The Variation Of The Insertion Loss With The Deflection at Different Initial Coupling Ratio, Single-Mode VFOCs and at 1310 nm.	93
5.16	The Variation of the Theoretical Insertion Loss with the Deflection at Different Initial Coupling Ratio.	94
5.17	Directivity Measurement Setup	95
5.18	The Variation of the Directivity with the Deflection at Different Initial Coupling Ratio, Single-Mode VFOCS and at 1550 nm.	96
5.19	The Variation of the Directivity with the Deflection at Different Initial Coupling Ratio, Multimode VFOCs and at 1550 nm.	97
5.20	The Variation of the Directivity with the Deflection at Different Initial Coupling Ratio, Single-Mode VFOCs and at 1310 nm.	98
A.1	Top View of the Bent Coupler.	106
A.2	The Position of the Tilt Angle after Certain Deflection.	106
A.3	The variation of the deflections with the bending angles.	108



B.1	Relationship between Power and Volt.	109
B.2	Experiment results that are obtained from the real-time panel display at various deflections, $d$ for the single-mode VFOC with initial coupling ratio of 10:90 at 1550 nm.	113
B.3	Experiment results that are obtained from the real-time panel display at various deflections, $d$ for the single-mode VFOC with initial coupling ratio of 50:50 at 1550 nm.	117
B.4	Experiment results that are obtained from the real-time panel display at various deflections, $d$ for the single-mode VFOC with initial coupling ratio of 30:70 at 1310 nm.	120
C.1	Experiment results that are obtained from the real-time panel display at various deflections, $d$ for the multimode VFOC with initial coupling ratio of 10:90.	123





#### **CHAPTER 1**

## **INTRODUCTION**

#### 1.1 Background

The development of fiber optic communication technology has increased tremendously with numerous applications. The applications are widespread involving voice, data and video transmissions and sensor application. As the world becomes more reliant on information technology, the need for a wider bandwidth data transmission has increased dramatically. The introduction of internet, video conferencing, Cable Television (CATV), Fiber-To-The-Home (FTTH) and Fiber-To-The-Office (FTTO) have also boosted more research on providing a larger information capacity (Yohji, 1990), (Kashima, 1995).

Concurrent with these, a lot of research and development have been done in several fields of optical fiber. These include the optical fiber networking system, characterization of single mode and multimode fiber and optical fiber devices such as polarization controller, modulators, power divider, passive filters, fiber amplifier and optical fiber coupler. Among all of the devices, optical fiber coupler is one of the important components in an optical fiber communication system.



The optical fiber coupler is a device that distributes light from a main fiber into one or more branches of fibers. This device split (demultiplex) or combine (multiplex) the optical signals passively (Mynbaev, 2001). Optical fiber couplers are important devices in fiber application such as high-speed data link systems, wavelength multiplexer-demultiplexer systems, coherent system, fiber sensors and fiber optic measurement systems. As the dynamic networks become more popular, such as the widely increasing deployment of metropolitan area network, fiber-to-the-home (FTTH) and cable TV networks, the demand for the fiber couplers has increased (Liu et al., 2005).

However, most of the fiber couplers can only provide a fixed optical coupling ratio which is unable to provide flexibility, reliability and scalability. Hence, the evolution of the telecommunications networks has created an increasing demand for the variable fiber couplers that are able to provide flexibility for optical network to maintain power equilibrium and maintain the quality of the network transmission (Liu et al., 2005), but there are some limitations on the existing variable fiber couplers such as unstable, small tuning range of coupling ratio, high in loss and costly. Hence, the need for a new designs of developing better performance variable fiber couplers. This coupler is known as a Variable Fiber Optic Coupler (VFOC). This project focuses on the design and development of the VFOC.



# 1.2 Problem Statement

The fabrication methods for the existence variable fiber couplers are mainly classified into two types, which are mechanical-polishing method (Digonnet et al., 1982) and Fused Biconically Tapered (FBT) method (Murphy et al. 1991). In mechanicalpolishing method, couplers are fabricated by polishing each of two fibers and placing the two polishing faces in contact. Disadvantages of this method are that the polishing technique needs to be extremely accurate; the coupler characteristics are unstable and high in cost (Noda et al., 1987).

In the FBT method, the variable fiber couplers are fabricated by thermally fusing two fibers and elongating them (Murakami et al., 1981). The tuning of the coupling ratio were produced by a slight lateral shift of the unpackaged coupler (Hill et al., 1981) or by varying the depth of insertion of the screw gauge within the package which lead to a bending of the coupler (Murphy et al. 1991) and or by moving one of the elongations stages along a circular arc centered directly at the bare coupler (Birks et al. 1992). Although the coupling ratio can be tuned for that devices, there are some problems such as difficulty in producing coupler with a high tuning resolution, high in loss and the possible changes in the coupling ratio due to packaging conditions. For example, when coupling ratio is tuned from 0% until 60%, the obtained excess loss is quite high, which is 0.55 dB (Hill et al., 1981). Birks et al. have improved the values, at 80% of tuning range of the coupling ratio, the excess loss can be reduced until 0.3 dB. However, the coupler can easily break as the bending is directly on the bare coupler.



For this reason, it is desirable to improve the performance of the variable fiber couplers

#### 1.3 Objectives

The objective of this research is to produce VFOC with a dynamic coupling ratio at a minimum loss and therefore, in the thesis, a design and development of the Variable Fiber Optic Coupler (VFOC) that consist of a fix Fused Biconically Tapered (FBT) coupler, which is fabricated from the FBT method is reported.

# 1.4 Scope of Work

There are two approaches taken in conducting this study, which are the software simulation and hardware implementations. The early stage of designing the VFOC utilizes the software. The selection of the software is based on the features that can help the simulation process of the device, and in this case the software used is BPM\_CAD. The aim of this simulation is to identify the device that can produce an optimum performance, and then to be implemented on the hardware, which are fabricated using the FBT method.

In the simulation, the parameter under study is design parameters such as bending angle, coupling length, core diameter and operating wavelength. The design parameters are important as they will affect the VFOC's performance. For example,

