UNIVERSITI PUTRA MALAYSIA

OPTICAL FIBER TWO-TAPER MACH-ZEHNDER INTERFEROMETER AS COMB FILTER FOR MULTIWAVELENGTH LASER GENERATION

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By

MAS IZYANI MD ALI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

April 2016

DEDICATION

To my family,

Mak
Abah
Zul Hilmi
Aisyah
Alya
Aatiqah
Amena

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

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Chairman : Professor Mohd Adzir Mahdi, PhD
Faculty : Engineering

Critical technologies such as fiber lasers, optical filters and optical amplifiers are particularly important for the implementation of wavelength division multiplexing (WDM) systems. In order to select specific multiple lasing wavelengths in fiber laser design, a wavelength-selective comb filter is usually included in the laser cavity. In recent times, Mach-Zehnder interferometer (MZI)-based on tapered-fiber structure has received notable attention due to its benefits such as simple and low-cost fabrication, easy tuning method and relatively wide tuning range. An in-line MZI that is formed by concatenating two identical abrupt fiber tapers enhances the side mode suppression ratio (SMSR) compared to the one achieved by a single taper. In addition, the two-taper MZI structure provides a simple method to obtain optical filter with narrow linewidth. The tunability by bending and stretching mechanism are also demonstrated and discussed. It is shown that by bending the fiber, a better tuning resolution was achieved (73.0 pm/µm) compared to stretching (93.0 pm/µm) and the process was reversible for the entire range. In most cases, MZI structure is made using conventional optical fibers, which works separately from the amplifying medium. However, these two elements can be integrated together in the laser cavity by forming the MZI using the active gain medium itself. In this thesis, the author proposed a tunable dual-wavelength erbium doped ring fiber laser with tapered-EDF as comb filter. It was found that the peak power and SMSR was at the highest value when using larger taper waist diameter (33 µm). The dimension of two-taper MZI directly affects the channel spacing (free spectral range). For larger channel spacing (30.3 nm), the two-taper EDF requires shorter taper waist length (5 mm). To obtain a smaller laser linewidth (≤ 1.0 nm), the interferometer length (spacing between two tapers) must be longer (>20 mm). Based on the findings, the dual-wavelength laser can be designed to suit different applications and needs. The capability of two-taper MZI as a wavelength selector in generating multiwavelength laser in hybrid Raman-Erbium gain medium was also investigated. The ring cavity was utilized in the fiber laser setup with 1455 nm pump laser to generate stimulated Raman scattering in the range of 1555 – 1565 nm (peak gain) which overlaps with Erbium gain spectrum. The lasing efficiency is improved and leads to the generation of longer wavelength lasers. The highest number of channel count of six lasers was recorded when using output coupling ratio of 20% with 15 mm taper waist length. The average SMSR was excellent with value of 59.5 dB with -1.63 dBm average peak powers. The demonstrated multiwavelength laser showed excellent peak power and wavelength stability for two hours at room temperature with the smallest variations of less than 0.08 dB and 0.02 nm respectively.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

GENTIAN OPTIK DUA-TIRUS METER GANGGUAN MACH-ZEHNDER SEBAGAI TURAS SISIR UNTUK PENJANAAN PANJANG GELOMBANG PELBAGAI

Oleh

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Teknologi kritikal seperti laser gentian, penapis optik dan penguat optik adalah sangat penting dalam pelaksanaan sistem pembahagian penggandaan panjang gelombang (WDM). Dalam usaha untuk memilih beberapa panjang gelombang pelaseran khusus dalam reka bentuk gentian laser, turas sisir panjang gelombang terpilih biasanya termasuk dalam rongga laser. Sejak kebelakangan ini, meter gangguan Mach - Zehnder (MZI) berasaskan kepada struktur tirus gentian optik telah mendapat perhatian yang ketara kerana manfaatnya seperti struktur yang ringkas dan kos fabrikasi yang rendah, kaedah penalaan yang mudah dan jangkauan penalaan yang agak luas. MZI dalam satu barisan yang dibentuk oleh dua struktur serupa tirus gentian yang curam meningkatkan nisbah penindihan sisi capaian (SMSR) berbanding dengan yang dicapai oleh tirus tunggal. Di samping itu, dua tirus struktur MZI ini menyediakan satu kaedah yang mudah untuk mendapatkan penapis optik dengan lebar spektrum yang sempit. Kaedah penalaan dengan mekanisme lenturan dan regangan juga ditunjukkan dan dibincangkan. Kajian menunjukkan bahawa dengan melenturkan gentian, resolusi penalaan yang lebih baik telah dicapai (73.0 pm / μm) berbanding regangan (93.0 pm / μm) dan proses ini adalah boleh diterbalikkan untuk keseluruhan julat. Dalam kebanyakan kes, struktur MZI dibuat menggunakan gentian optik konvensional , yang bekerja secara berasingan daripada medium penguat itu. Walau bagaimanapun, kedua-dua elemen tersebut boleh diintegrasikan bersama-sama dalam rongga laser dengan menubuhkan MZI menggunakan medium gandaan aktif itu sendiri. Dalam tesis ini, penulis mencadangkan dua panjang gelombang boleh tala erbium terdop laser gentian dalam struktur bulatan (EDRFL) dengan tirus - EDF sebagai turas sisir. Kami mendapati bahawa puncak kuasa dan SMSR adalah pada nilai yang paling tinggi apabila menggunakan diameter garis pusat bahagian tengah tirus gentian yang lebih besar (33 μm). Dimensi dua tirus MZI memberi kesan langsung kepada jarak saluran (julat spektrum bebas). Untuk jarak saluran yang lebih besar, dua tirus EDF memerlukan panjang tirus bahagian tengah yang pendek. Untuk mendapatkan laser yang

mempunyai lebar spektrum yang lebih kecil , panjang interferometer itu (jarak antara dua tirus) mestilah lebih panjang. Berdasarkan dapatan kajian, laser dua panjang gelombang boleh direka untuk disesuaikan dengan aplikasi dan keperluan yang berbeza. Keupayaan dua tirus MZI sebagai pemilih panjang gelombang dalam menjana panjang gelombang pelbagai laser medium gandaan hibrid Raman-Erbium juga dikaji. Struktur bulatan telah digunakan dalam persediaan laser gentian dengan pam laser 1455 nm untuk menjana serakan Raman dirangsang (SRS) dalam lingkungan 1555-1565 nm (puncak gandaan) yang bertindih dengan spektrum gandaan Erbium. Kecekapan laser bertambah baik dan membawa kepada penjanaan panjang gelombang laser yang lebih panjang. Bilangan tertinggi kiraan saluran sebanyak enam laser telah dicatat apabila menggunakan nisbah gandingan kelauaran sebanyak 20% dengan menggunakan panjang tirus bahagian tengah 15 mm. Purata SMSR adalah sangat baik dengan nilai 59.5 dB dan -1.63 dBm purata kuasa puncak. Laser panjang gelombang pelbagai menunjukkan kestabilan puncak kuasa dan panjang gelombang yang sangat baik selama dua jam pada suhu bilik dengan variasi yang sangat kecil masing-masing kurang daripada 0.08 dB dan 0.02 nm.

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I certify that a Thesis Examination Committee has met on 21 April 2016 to conduct the final examination of Mas Izyani bt Md Ali on her thesis entitled "Optical Fiber Two-Taper Mach-Zehnder Interferometer as Comb Filter for Multiwavelength Laser Generation" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

ASE	Amplified spontaneous emission
BFA	Brillouin fiber amplifier
DCF	Dispersion compensating fiber
DWFL	Dual-wavelength fiber laser
DWDM	Dense wavelength division multiplexing
EDF	Erbium-doped fiber
EDFA	Erbium-doped fiber amplifier
EDRFL	Erbium doped ring fiber laser
FSR	Free spectral range
FHB	Fiber holding block
MZI	Mach-Zehnder interferometer
OSA	Optical spectrum analyser
OPM	Optical power meter
PCE	Power conversion efficiency
PC	Polarization controller
PHB	Polarization hole burning
RFA	Raman fiber amplifier
RPU	Raman pump unit
RIN	Relative intensity noise
SMF	Single-mode fiber
SOA	Semiconductor optical amplifier
SMSR	Side mode suppression ratio
SHB	Spectral hole burning
SOP	State of polarization

TBF	Tunable bandpass filter
WDM	Wavelength division multiplexing
WSC	Wavelength selective element

CHAPTER 1

INTRODUCTION

1.1 Overview

Fiber optic communication is attractive due to its extraordinary capability to carry information in capacity far greater than its competitors such as coaxial cables and microwave links. The primary reason that optical fibers have very much larger information-carrying capacity than other media is because they carry light. Light in a glass medium can carry more information over longer distances than electrical signals can carry in a copper or coaxial medium or radio frequencies through a wireless medium. In addition, optical fibers are inexpensive to produce, do not conduct electricity which makes them immune to disturbance by lightning storms, and other electromagnetic signals (except nuclear radiation), do not corrode, and are of small size. The research on fiber optic began as early as 1960s. However, it is not until 1970s that the breakthrough came in when scientists in Corning Incorporated Dr. Robert Maurer, Donald Keck, and Peter Schultz created a fiber with a measured attenuation of less than 20 dB per km [1]. The three scientists' work is recognized as the discovery that led the way to the commercialization of optical fiber technology. The rapid development in fiber optic fabrication technology finally allows for the fiber losses to drop to less than 0.2 dB/km [2]. Since then, the technology has advanced tremendously in terms of performance, quality, consistency, and applications.

Within the last twenty years, fiber-based devices have been developed extensively for employment in filters, sensors, amplifiers and lasers. This is because the potential bandwidth of the optical fiber is only limited by the electronics in the type of multiplexing/de-multiplexing scheme employed. The demand for more capacity over the last decades has soared due to the amplifying need from the internet users for high bandwidth applications such as high definition video, an increase in the number of gadgets and devices that use broadband connections, as well as the implementation of internet protocol television. Capacity of optical fiber systems increased from 0.1 GB/s in 1980 to well over 100 Tb/s presently [3].

In order to cope with the wavelength demand as the channel for transmitting data increases, the wavelength division multiplexing (WDM) and dense wavelength division multiplexing (DWDM) was then introduced to increase capacity without requiring the deployment of new fiber optic cables [4][5]. This technology soared primarily due to the excellent applicability of WDM which is based on the utilization of the wide low-loss spectrum region in optical fibers. The low loss region of a single-mode fiber extends over wavelengths from roughly 1.2 to 1.6 µm, which is an optical bandwidth of more than 30 THz. The WDM and DWDM are however, working with the same principle by combining multiple signal wavelengths onto a single optical fiber. The only difference is their inter channel spacing and number of channel involves. The improvement was necessary to transmit large number of relatively close-spaced channels along an optical fiber. Instead of 8 channels provided by the conventional WDM systems, the DWDM system would typically provide 40 channels with 100 GHz spacing or 80 channels of 50 GHz spacing.

Research efforts in DWDM optical device technology have led to the emergence of all-optical fiber networks that promise to reduce the maintenance cost and increase flexibility. The critical technology particularly important for the implementation of WDM systems are fiber lasers, optical filters and optical amplifier. Fiber lasers are of particular interest due to its advantages compared to other types of lasers such as semiconductor laser or solid state laser. They include fiber compatibility, low intensity noise, high output power, high optical quality and narrow linewidth. The underlying principle to produce fiber laser is through a special fiber optic arrangement which utilizes a doped rare earth material acting as the gain media. The doped fiber is arranged together with other optical components to form a ring or linear resonator. The doped fibers commonly used are erbium, ytterbium, thulium or neodymium [6]–[11]. Other type of fiber laser which gain popularity is Raman fiber laser (RFL) [12]–[14], which utilizes stimulated Raman scattering (SRS) effects to shift the wavelength of light from an input pump laser to another desired wavelength, 13.2 THz or 100 nm wavelength separation between pump light and laser output. The first continuous wave (CW) Raman laser using an optical fiber as the gain medium has been demonstrated in 1976 [15]. By properly selecting the pump wavelength and by cascading the pumps through several Raman stoke shifts; devices at almost any wavelength can be made. The details on RFL will be further discussed in Chapter 2.

The most important device for the generation of multiwavelength fiber laser is wavelength selective element. In order to select specific multiple lasing wavelengths, a wavelength-selective comb filter is usually included in the laser cavity [16]–[18]. Up to now, there are many methods reported for all-fiber comb filters, such as twincore fiber [19]–[21], Fabry Perot filter [22], Lyot filter [23], fiber grating [24], Sagnac loop interferometer [25], and Mach–Zehnder interferometer (MZI) [26]. Among these, MZI has exhibited remarkable advantages such as broad wavelength operation range , insensitivity to environmental changes, ease of fabrication at relatively low cost as well as high reliability and stability [27][28]. In recent times, MZI-based on tapered-fiber structure has received notable attention due to its benefits such as simple and low-cost fabrication, easy tuning method, relatively wide tuning range as well as high stability [28], [29].

1.2 Problem statement

The ability of tapered fiber application as comb filter is favourable. With proper fabrication technique, tapered fiber possesses low insertion loss and the parameters can be tailored simply by changing the length of tapered waist. Furthermore the fabrication of tapered fiber is very simple and low cost.

Typically, MZI structure is made using conventional optical fibers, which works separately from the amplifying medium in a fiber laser configuration. Such arrangement increases the complexity and size of the laser system, in addition to the supplementary cost required to prepare the two individual components. Integration of MZI, tapered fiber with gain medium could prove to be a grand idea, however, no research has been done to prove that multiwavelength laser is possible with this integrated device and whether it is possible to illicit any other features from such a simple structure.

These two elements can be integrated together in the laser cavity by forming the MZI using the active gain medium itself. In other words, gain medium such as erbium doped fiber (EDF) or any doped fiber can be tapered and used as wavelength selective element as well as gain medium for laser generation. This will lead to a compact and cost-effective fiber laser design. In this thesis, we propose a dual-wavelength erbium-doped fiber laser using tapered EDF as comb filter. A study is performed to evaluate other feature of the laser such as wavelength tunability. We also investigated the generation of multiwavelength laser using tapered fiber using Hybrid Raman-Erbium as gain media.

1.3 Objectives

The overall objective of this thesis is to investigate the feasibility of tapered fiber as a comb filter for the generation of multiwavelength fiber lasers. The specific objectives are listed as follows:

1. To design and develop a Mach-Zehnder interferometer filter based on tapered fiber
2. To design and develop a dual wavelength tunable Erbium-doped fiber laser using tapered-EDF as comb filter.
3. To design and develop multiwavelength fiber laser utilizing hybrid Raman-Erbium gain medium.

1.4 Scope of work

Figure 1.1 describes the work involve in this study on fiber laser. Both dual and multiwavelength fiber laser are presented in this work. In dual-wavelength fiber laser, Erbium doped fiber is used as the gain medium. The wavelength selective element proposed in this work is tapered-EDF. In generation of multiwavelength fiber laser, we presented by using hybrid Raman-EDF as gain medium utilizing tapered single mode fiber (SMF) as wavelength selective element.

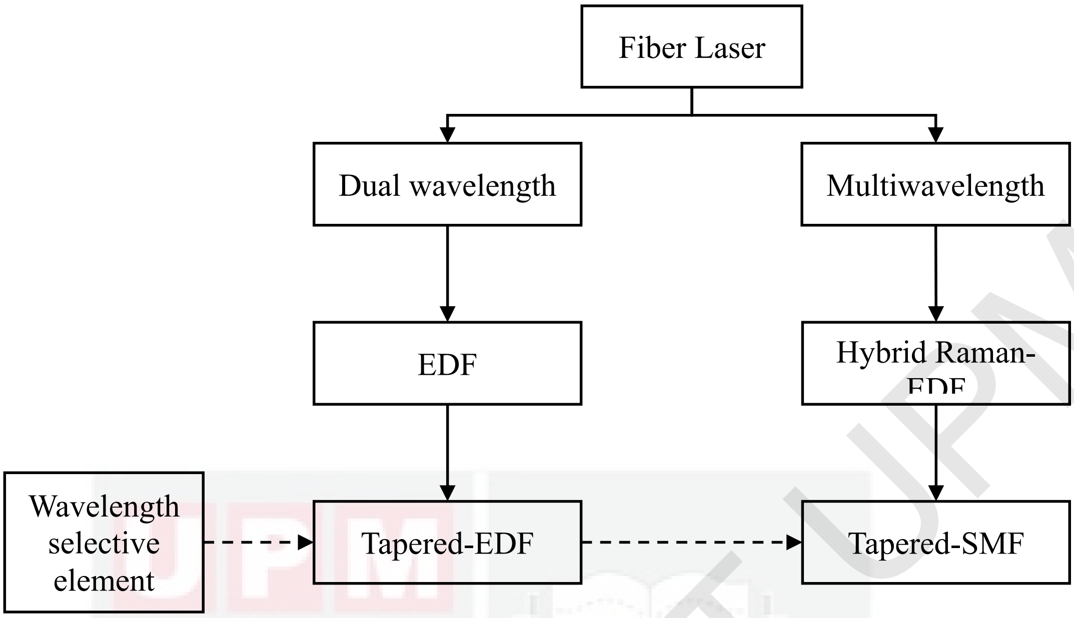

Figure 1.1 : Scope of work

1.5 Thesis outline

This thesis comprises of six chapters. Chapter 1 includes the introduction, problem statement, objectives and scope of work involved in this research. Chapter 2 presents the theoretical background and review on the previous reported research findings in this area. The fabrication of tapered fiber and its characterization will be discussed in Chapter 3. Chapter 4 presents the work on Erbium doped fiber laser utilizing tapered fiber as comb filter in generation of tunable dual-wavelength laser. In Chapter 5, the work on Hybrid Raman-Erbium on multiwavelength fiber laser is discussed in details. Finally, Chapter 6 summarizes the conclusions, research contributions and future recommendations for this research.

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