STABLE MULTIWAVELENGTH ERBIUM-DOPED RANDOM FIBER LASER

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To my beloved families and friends

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ABSTRACT

Multiwavelength fiber lasers which consist of equally-spaced frequency components have found many applications and that includes as light sources for optical communication systems. One of the techniques available to generate such multiple wavelengths is random fiber lasers. Despite simplicity in structure due to the avoidance of mirrors in random fiber lasers, the number of comb lines generated is rather limited with only four comb lines are generated within 3 dB flatness at the 60 mW pump power. In optical communication systems, such a limitation in the comb lines could be a hindrance for the attainment of high-speed data communication due to the lack of light sources. Aspired to solve the problems and bring random multiwavelength to new heights, performances of multiwavelength random fiber lasers are improved in this thesis work. Based on the random Rayleigh scattered feedback of a 25 km long single-mode optical fiber, multiwavelength lasers are successfully generated. The linear cavity in which one end is formed by a mirror and the other end by the random Rayleigh scattered feedback is able to generate 27 laser lines within 3 dB flatness at the pump power of 350 mW. In addition, the laser lines generated are also stable with power fluctuations less than 0.6 dB over an hour duration. All in all, the study in this work is found to be effective in elevating the performances of multiwavelength random fiber lasers to further heights.

ABSTRAK

Laser gentian multi-gelombang yang terdiri daripada komponen frekuensi yang sama jarak telah menjumpai banyak aplikasi dan termasuk sebagai sumber cahaya untuk sistem komunikasi optik. Salah satu teknik yang boleh digunakan untuk menjana gelombang panjang berbilang adalah laser gentian rawak. Walaupun kesederhanaan dalam struktur disebabkan pencegahan cermin dalam laser gentian rawak, bilangan garis laser yang dihasilkan agak terhad dengan hanya empat garisan laser dihasilkan dalam kebuk 3 dB pada kuasa pam 60 mW. Dalam sistem komunikasi optik, batasan dalam garisan laser boleh menjadi penghalang untuk mencapai komunikasi data berkelajuan tinggi kerana kekurangan sumber cahaya. Melalui ilham untuk menyelesaikan masalah dan membawa multi-gelombang rawak ke tahap yang baru, persembahan laser gentian rawak multi-gelombang diperbaiki dalam kerja tesis ini. Berdasarkan kepada reaksi Rayleigh secara rawak yang menyebarkan gentian optik tunggal mod 25 km panjang, laser multi-gelombang dihasilkan dengan jayanya. Rongga bergaris datar di mana satu hujung dibentuk oleh cermin dan hujung yang lain oleh maklum balas Rayleigh yang berselerak rawak dapat menghasilkan 27 garisan laser dalam 3 dB kesamarataan pada kuasa pam 350 mW. Di samping itu, garisan laser yang dihasilkan juga stabil dengan turun naik kuasa kurang daripada 0.6 dB dalam tempoh satu jam. Secara keseluruhannya, kajian dalam kerja ini didapati berkesan dalam meningkatkan prestasi multi-gelombang laser gentian rawak ke tahap yang lebih tinggi.

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LIST OF SYMBOLS AND ABBREVIATIONS

DWDM	-	Dense wavelength division multiplexing
EDFA	-	Erbium-doped fiber amplifier
FWM	-	Four-wave mixing
EDRFL	-	Erbium-doped random fiber laser
SPM	-	Self-phase modulation
XPM	-	Cross-phase modulation
SRS	-	Stimulated Raman Scattering
SBS	-	Stimulated Brillouin Scattering
RS	-	Rayleigh Scattering
HNLF	-	Highly nonlinear fiber
SMF	-	Single mode fiber
N	-	Refractive index
Ω	-	Frequency of optical waves
I	-	Intensity of optical waves
n_2	-	Refractive index of silica fiber
L	-	Length of optical fiber
$\Delta\varphi_{SPM}$	-	Nonlinear phase shift
M	-	The number of new frequencies generated
Λ	-	Propagating wavelength
A_{eff}	-	Effective area of the light mode inside the fiber
P	-	Applied optical power
N	-	The number of launched signal into the fiber
C	-	Velocity light in the vacuum
D_x	-	Degeneracy factor
A	-	Fiber losses
H	-	FWM efficiency
$\Delta\beta$	-	Propagation constant phase mismatch

OLT - Optical line terminal

WDM - Wavelength division multiplexing

EDF - Erbium-doped fiber

PC - Polarization controller

PMF - Polarization maintaining fiber

CW - Clockwise

CCW - Counter clockwise

T - Transmission spectrum

B - PMF birefringence value

ASE - Amplified spontaneous emission

FP - Fabry-Perot

DFB - Distributed feedback

RDFB - Random distributed feedback

RIN - Relative intensity noise

DCF - Dispersion compensating fiber

OSA - Optical spectrum analyzer

GeO_2 - Germanium Dioxide

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CHAPTER 1

INTRODUCTION

1.1 Background study

The internet is very important nowadays to the extent that it becomes an integral part of the life. In the past, people have more difficulty to find information and do their job. For example, students have to go to the library and read different books to know the details of a lesson in the class. Likewise, businessmen in another example, do their advertising physically via distributing flyers to their customers. However, with the inception of internet, it is easier for the people now to search for information and carry out their job. Students nowadays search engine site to become knowledgeable in a certain topic and businessmen advertise their products or services through advertisement in their company website. With the advantage of the internet, the demand for bandwidth gets more enormous and the high-speed internet becomes a necessity as a result for the current lifestyle. In order to cater for the high-speed internet, dense wavelength division multiplexing (DWDM) system is employed so that voice, video and data signals can be uploaded and downloaded at high data rates. DWDM system is a technology where a combination of many channels takes place for signal transmission along an optical fiber. The channels spacing in DWDM system is a fraction of nanometer, therefore more channels can be accommodated in the optical fiber and subsequently the high-speed internet can be realized.

Figure 1.1 illustrates a typical configuration for a DWDM system. A basic DWDM system consists of an optical transmitter, add-drop multiplexer, transmission line and receiver. In the optical transmitter, several channels which have different wavelengths to avoid mutual interference are launched and they are combined into a single optical fiber through an optical multiplexer. The combination is implemented so that only a single optical fiber is laid out for signal transmission. Along the transmission line which is the optical fiber, few optical components are located such as optical amplifiers, dispersion compensators and add drop multiplexers. The function of optical amplifiers is to keep the power of the channels at a certain level, whereas dispersion compensators serve for mitigation of dispersion effect in optical fibers. In order to add or drop channels, add drop multiplexers are placed at nodes along the transmission line. In the optical receiver, the multiplexed channels are separated by an optical demultiplexer. The information carried out by the channel is recovered by photo-detectors in the optical receiver.

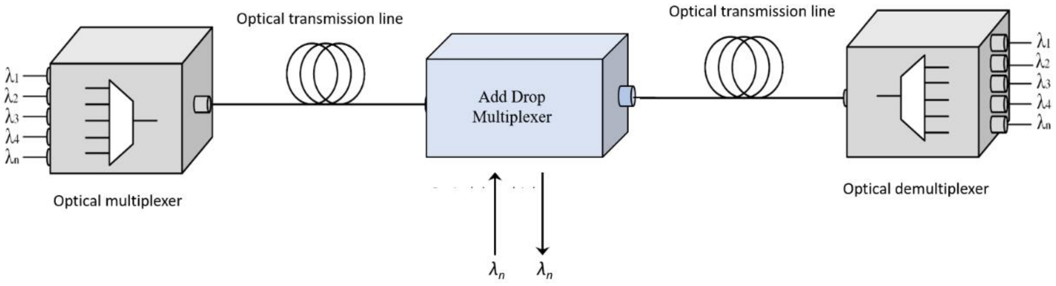

Figure 1.1: Typical DWDM system.

1.2 Problem statement

A typical DWDM system requires multiple laser diodes to generate laser sources. This necessity needs very high cost for the implementation and the maintenance purposes. This happens because the system being more complicated as each laser diode requires a controller for current and temperature parameters. Therefore, a large number of controllers are essential for the operation when typical DWDM system is implemented. Figure 1.2 shows a typical transmitter in DWDM system. It needs a large number of laser diodes with different wavelength as the carrier for the optical transmission.

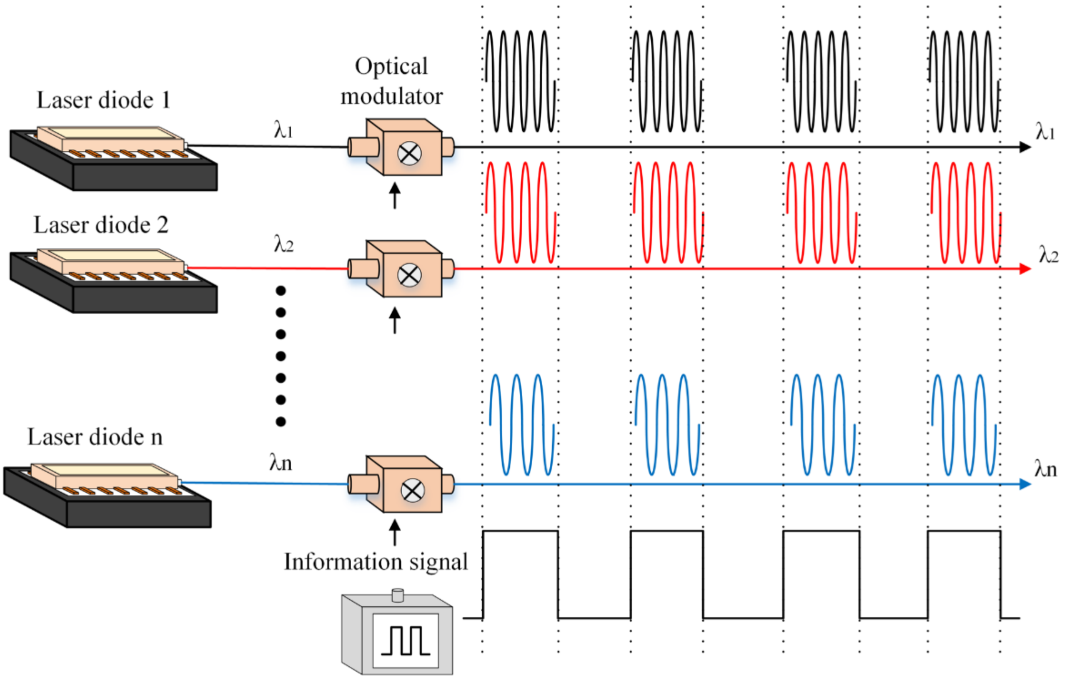

Figure 1.2: Typical transmitter utilized in DWDM system.

In order to cater for the problem of laser diodes complexity, a multiwavelength source is used. Figure 1.3 shows the illustration of DWDM transmitter utilizing a multiwavelength source. Instead of using many laser diodes, this enhanced DWDM transmitter exploits a multiwavelength source to generate carriers for the transmitted channels. However, it needs an optical demultiplexer at the transmitter side to separate the carrier in the multiwavelength source. On the plus side though, the avoidance of temperature and current controller for each laser diode in the typical DWDM system in general outweighs the requirement for an extra optical demultiplexer in the enhanced DWDM system. Therefore, DWDM transmitter utilizing multiwavelength source is an interesting alternative to replace the existing technology.

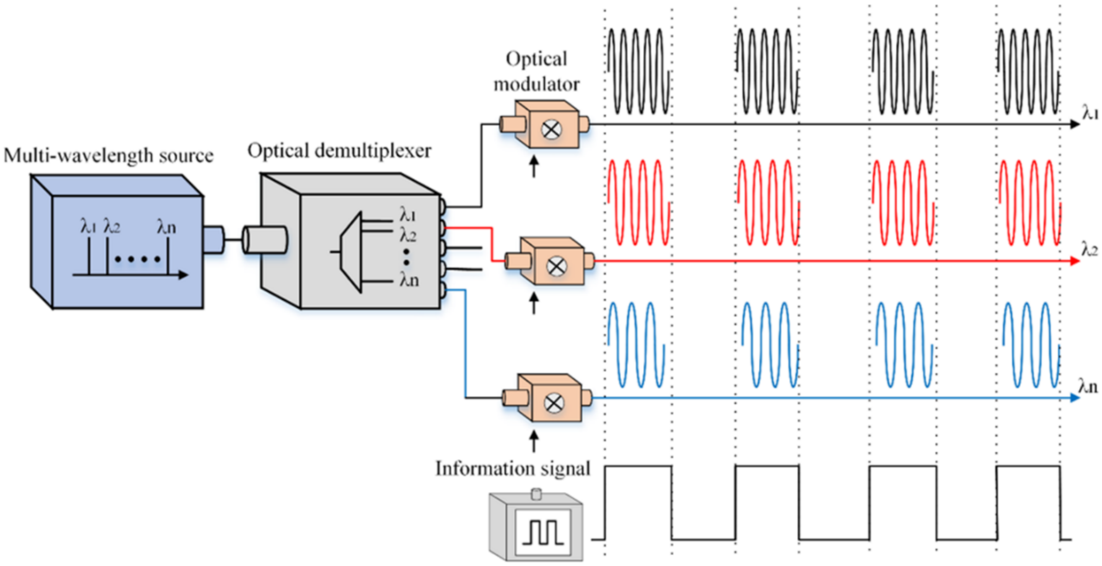

Figure 1.3: Transmitter in DWDM system utilizing multiwavelength source.

Multiwavelength source has been introduced by many researchers and one of the prominent methods is by using random distributed feedback or random laser [1]-[5]. In this technique, the laser structure is simpler and more compact than conventional fiber lasers as a result of the avoidance of external mirrors in the laser cavity. Despite the simpler structure of random fiber lasers, the comb lines generated are not flat and stable have been presented in [1]. At the 60 mW pump power, four comb lines are generated within 10 dB flatness as illustrated in Figure 1.4 [1]. Multiwavelength flatness here is measured by the number of channels that exist within 3 dB from the highest power of the spectrum. Typically, in communication system, the standard power discrepancy allowed between the channels is around 3 dB and below. In DWDM optical communication systems, such a lack of flatness can lead to the efficiency degradation as a result of gain mode competition in the erbium-doped fiber amplifier (EDFA) [5]. Besides the flatness issue, the comb lines are also not stable within time. Multiwavelength stability here refers to the stability of the channel peak power over time. For that reason, there is a need to develop a new technique such that random fiber lasers do not only operate without external mirrors but also possess flat and stable comb lines.

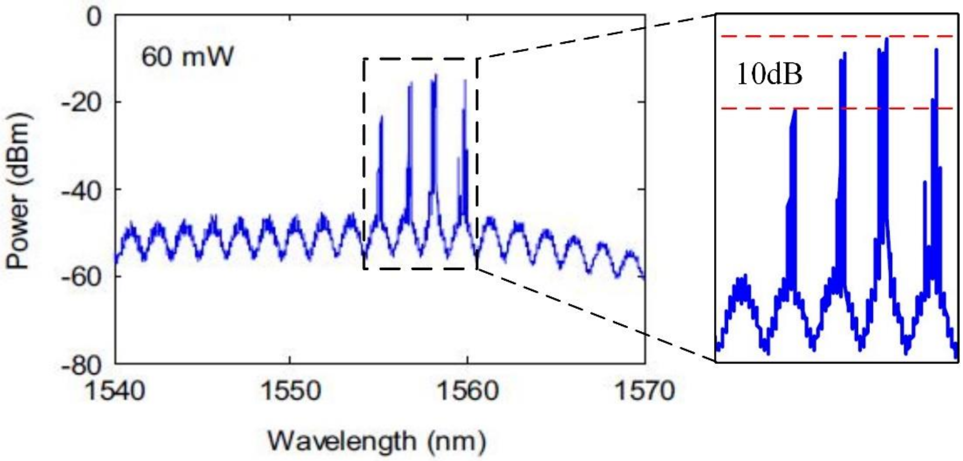

Figure 1.4: Flatness and stability of multiwavelength laser in [1].

It is known that random Rayleigh scattered-light and gain mode competition in the EDFA gives rise to the instability of multiwavelength fiber laser. In this work, it is believed that introducing nonlinear effect of four-wave mixing (FWM) in the laser cavity will enhance the stability and flatness of the multiwavelength random fiber laser [5]-[13].

1.3 Research objectives

The main objective of this research work is to develop a stable and flat multiwavelength erbium-doped random fiber laser (EDRFL). More specific objectives are:

(i) To develop an EDFA as the gain medium in the laser cavity.
(ii) To develop a Sagnac filter as the comb filter for the multiwavelength laser.
(iii) To investigate the impact of fiber nonlinearity of FWM as a stabilizer for the multiwavelength EDRFL.

1.4 Research scopes

The research work done in this thesis is limited by the following research scope;

(i) Generation of multiwavelength fiber lasers in general can be categorized into two methods; conventional fiber lasers and random fiber lasers. In this work, the multiwavelength lasers are generated by a random fiber laser that utilizes a half-opened and linear laser cavity.

(ii) Various types of gain mechanism such as EDFA, Raman and Brillouin gain can be used to generate multiwavelength random fiber lasers. This work however focuses on EDFA in order to provide amplification for the oscillating signals.

(iii) There are many types of comb filter that can be utilized in the laser cavity to produce the multiwavelength lasers such as Mach-Zehnder interferometer (MZI), Fabry-Perot interferometer, Lyot and Sagnac filter. The comb filter used in the scheme is Sagnac filter due to its simplicity.

(iv) Stability of multiwavelength fiber lasers can be provided by including a nonlinear gain medium in the laser cavity. In this work, a highly nonlinear fiber (HNLF) is utilized to mitigate the gain mode competition introduced by the EDFA.

1.5 Research contributions

This research work contributes to a new design of multiwavelength EDRFL that can enhance the performances of stability and flatness. The more details of the contributions are:

(i) The formation of a new design of multiwavelength EDRFL. The new design is attributed by the introduction of nonlinearity mechanism in the existing laser cavity. The new design consists of a half-opened linear cavity in which one end is formed by a mirror and the other end by the random Rayleigh scattered feedback of a long single-mode fiber.

(ii) The stability enhancement of multiwavelength EDRFL. Previous designs have an issue of stability resulting from the random nature of Rayleigh scattered feedback and gain mode competition of the EDFA. With this new design, it is able to generate laser lines with power fluctuations of less than 0.6 dB over an hour duration.

(iii) The flatness improvement of multiwavelength EDRFL. Multiwavelength lasers in the previous designs are not flat due to chaotic behaviour of the random distributed feedback and EDFA gain mode competition. With the introduction of nonlinear gain medium in the laser cavity, the proposed design is capable to generate 27 laser lines within 3 dB flatness at the pump power of 350 mW.

1.6 Research outline

In Chapter 1, some background for DWDM optical communication system is introduced. This includes the system requirement to satisfy the speed for data transmission, basic operating principle and some disadvantages that need to be addressed. Problem statements and research objectives are also explained in this chapter.

In Chapter 2, some studies have been done on fiber nonlinearities which are self-phase modulation (SPM), cross-phase modulation (XPM), FWM, Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS). Review on basic principle of EDFA and Sagnac filter are also covered in this chapter. Random fiber laser in comparison to conventional fiber laser is explained as well as Rayleigh Scattering (RS) process in the fiber and its gain mechanisms. Related work in random fiber lasers is also discussed.

Research methodology is reported in Chapter 3. It starts with optical devices characterization; EDFA and Sagnac filter characterization. Experimental setup in generating stable multiwavelength EDRFL and its operating principle are described in this chapter.

Experimental results for this work are discussed in Chapter 4. Starting with comparison of output spectrum with HNLF and without HNLF in the scheme, it then continues with the impact of different single mode fiber (SMF) length as well as difference in location of EDFA upon the performances of the multiwavelength laser.

Discussion of the proposed scheme performances; specifically, spectrum evolution, stability, flatness and lasing threshold are explained thoroughly in this chapter.

Finally, for Chapter 5, conclusion and some recommendations for this work in the future are discussed.

CHAPTER 2

LITERATURE REVIEW

This chapter starts with some studies on fiber nonlinearities which include SPM, XPM, FWM, SRS and SBS. Then, reviews on EDFA, Sagnac filter, random fiber laser and recent developments related to the random fiber laser are presented in this chapter.

2.1 Fiber nonlinearities

Similar to other dielectrics, optical fibers behave in a nonlinear fashion when high intensity electromagnetic fields are applied to them. The first discovery of nonlinear phenomena happened in 1961, about one year after the inception of laser in 1960. In that nonlinear experiment, fiber nonlinearities in a quartz crystal was utilized to convert the incident red light of a ruby laser into ultraviolet beam. Despite having low losses, optical fibers which are based on silica-glass material have a small nonlinear co-efficient, therefore triggering nonlinear phenomena becomes a big challenge. However, the advancement of laser and fiber technologies in recent decades helps revealing nonlinear phenomena in optical fibers. Laser nowadays can produce high output power and the high power can excite the nonlinear phenomena in optical fibers. Likewise, the optical fiber itself has undergone progress. The optical fibers currently have a smaller effective area due to a smaller core and this contributes to high intensity of propagating optical signal. In essence, the developments of lasers and optical fibers have spurred the advancement of nonlinear phenomena in optical fibers.

The fiber nonlinearities fall into two categories; nonlinear refraction and stimulated inelastic scattering. The nonlinear refraction comes from the modulation of fiber refractive index due to the intense incident optical fields. As a result of the modulation, the input optical fields have a change in phase and new optical frequencies are generated when phase matching condition is realized. Examples of fiber nonlinearities that fall under this category are SPM, XPM and FWM. On the other hand, under the category of stimulated inelastic scattering, the phenomena happen from the interaction of optical photons with phonons. Resulting from the interaction, frequency downshift occurs due to the energy losses of input optical fields in the medium. Two optical nonlinearities of SRS and SBS fall under this category.

2.1.1 Self-phase modulation

Two main factors that affect refractive index of optical fibers are the frequency of optical fields and the optical intensity. These factors are related to the refractive index through the well-known Kerr effect and the refractive index, n can be written as [14]

$$n(\omega, I) = n(\omega) + n_2 I \tag{2.1}$$

where ω and I are the frequency and intensity of the optical waves respectively. n_2 which stands for nonlinear refractive index of silica fibers is on the order of 10^{-20} m^2/W and the value can be varied when the silica fibers are doped with other elements such as GeO_2. It is known that the refractive index affects the speed of propagating optical waves. When the optical intensity influences the refractive index, then the phase of the propagating wave changes as well. For the case of SPM, the intensity of the wave itself changes the refractive index and it ends up changing its own phase after propagating through the optical fiber. The phase shift accumulated along a length of the fiber, L resulting from this effect is known as nonlinear phase shift, $\Delta\varphi_{SPM}$ which can be written as [14]

$$\Delta\varphi_{SPM} = \gamma PL \tag{2.2}$$

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