NEW TECHNIQUES FOR MULTIPLE WAVELENGTH FIBER LASER GENERATION BASED ON EDFA AND TDFA

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To my beloved family

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ABSTRACT

Multiple wavelength fiber laser (MWFL) can be a potential source for microwave generation as the conventional microwave generator have several issues in generating high frequency. In order to be such source, the MWFL must have the following criterion; a great number of comb lines, a compact design, adjustable and switchable wavelength spacing, as well as stable MWFL. Four main research studies are successfully demonstrated in efforts to improve the performance of MWFL either based on erbium doped fiber amplifier (EDFA) or thulium doped fiber amplifier (TDFA). The first study is related to a numerical analysis of Brillouin erbium fiber laser (BEFL). In this study, the elements of EDFA and stimulated Brillouin scattering (SBS) effect are thoroughly investigated. It is found that the optimum length of erbium doped fiber (EDF) is 10 m and the residual waves exist in the forward propagation. These findings successfully generate up to 10 Stokes lines. The second research work is related to an experimental study on the four-wave mixing cascades (FWMC) seeded by a BEFL. In the experiment, the Brillouin pump (BP) wavelength is varied to optimize the number of comb lines. Experimental results show that up to 80 comb lines is generated when the BP wavelength is varied at 1560 nm. In the third research work, an experimental setup of dual-wavelength Brillouin thulium fiber laser (BTFL) with an adjustable Brillouin frequency spacing (BFS) is designed. The proposed design incorporates a micro air gap in the BTFL cavity. This study successfully generates dual wavelength with single-, double-, and triple- BFS which has wavelength spacing of 0.084 nm, 0.166 nm, and 0.254 nm, respectively. The fourth research work is associated with the generation of multiple wavelength thulium-doped fiber laser (TDFL) by splicing single mode fiber (SMF) at both ends of 2.5 m two-mode step index fiber (TMSIF). The proposed scheme successfully generates up to 8 stable laser lines with wavelength spacing of 0.8 nm. Based on the experimental results of BTFL and TDFL, the proposed scheme is able to generate a microwave signals for 10 GHz, 20 GHz, 30 GHz, and 100 GHz region, respectively.

ABSTRAK

Laser gentian panjang gelombang berbilang (MWFL) berpotensi menjadi sumber kepada penjanaan gelombang mikro dimana penjanaan gelombang mikro sedia ada mempunyai masalah dalam menjana frekuensi yang tinggi. Untuk menjadi sumber tersebut, MWFL mesti mempunyai kriteria berikut; garisan sesikat yang banyak, reka bentuk yang ringkas, jarak panjang gelombang boleh laras, dan MWFL yang stabil. Empat kajian penyelidikan utama berjaya ditunjukkan dalam usaha memperbaiki pencapaian MWFL sama ada berdasarkan pengganda fiber berdop-erbium (EDFA) atau pengganda fiber berdop-thulium (TDFA). Kajian pertama adalah mengenai analisis berangka laser gentian Brillouin-erbium (BEFL). Dalam kajian ini, elemen EDFA dan kesan penyerakan Brillouin rangsangan (SBS) disiasat secara mendalam. Kajian mendapati panjang optima bagi fiber berdop-erbium (EDF) ialah 10 m dan wujudnya lebihan gelombang. Penemuan ini berjaya menghasilkan 10 bilangan garisan Stokes. Kajian kedua berkaitan eksperimen lata pergaulan empat gelombang (FWMC) daripada BEFL. Panjang gelombang pam Brillouin (BP) divariasikan untuk menambah baik bilangan garisan sesikat. Sebanyak 80 bilangan garisan sesikat dijana apabila panjang gelombang BP divariasikan pada 1560 nm. Kajian ketiga pula, membangunkan eksperimen bagi dua panjang gelombang laser gentian Brillouin-erbium (BTFL) dengan jarak frekuensi Brillouin (BFS) boleh laras. Reka bentuk tersebut menggabungkan jurang udara mikro ke dalam konfigurasi BTFL. Kajian ini berjaya menjana BFS yang mempunyai jarak tunggal (0.084 nm), dua kali ganda (0.166 nm), dan tiga kali ganda (0.254 nm). Kajian penyelidikan keempat berkaitan penjanaan panjang gelombang berbilang laser gentian berdopkan thulium (TDFL) dengan menyambungkan gentian mod tunggal (SMF) di setiap hujung gentian dua mod (TMSIF) yang panjangnya ialah 2.5 m. Ia berjaya menjana 8 garisan laser yang stabil dengan jarak panjang gelombang ialah 0.8 nm. Berdasarkan keputusan eksperimen BTFL dan TDFL, reka bentuk yang dicadangkan berkebolehan menjana frekuensi di rantau 10 GHz, 20 GHz, 30 GHz dan juga 100 GHz.

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A_{eff}	-	Effective area
b	-	Polarization effect
c	-	Speed of light in vacuum
E	-	Electric field
g_B	-	Brillouin gain
h	-	Planck constant
L_{EDF}	-	Erbium doped fiber length
L_{EFF}	-	Effective length
L_{SMF}	-	Single mode fiber length
N_1	-	Ground energy state
N_2	-	Metastable energy state
N_T	-	Total population of Erbium ion
P_{ASE}	-	Amplified spontaneous emission power
P_{BP}	-	Brillouin pump power
P_{EDF}	-	Erbium doped fiber pump power
P_S	-	Stokes power
P_{TDF}	-	Thulium doped fiber pump power
P_{th}	-	Threshold power
v_{EDF}	-	Erbium doped fiber pump frequency
v_{BP}	-	Brillouin pump frequency
α	-	Attenuation or fiber loss
$\Delta\beta$	-	Linear phase-mismatch
$\Delta\lambda$	-	Wavelength spacing
Δv	-	Noise bandwidth
γ	-	Fiber nonlinearity
κ	-	Total phase-mismatch

τ_{21}	-	Spontaneous emission lifetime
λ	-	Wavelength
λ_0	-	Zero-dispersion wavelength
ω	-	Angular frequency
ϕ	-	Phase shift
5G	-	Fifth generation
ASE	-	Amplified spontaneous emission
BEFL	-	Brillouin-erbium fiber laser
BFL	-	Brillouin fiber laser
BFS	-	Brillouin frequency spacing
BGM	-	Brillouin gain medium
BP	-	Brillouin pump
BTFL	-	Brillouin-thulium fiber laser
C-band	-	Conventional-band
CCW	-	Counter-clockwise
CFBG	-	Chirped fiber Bragg grating
CIR	-	Circulator
CW	-	Clockwise
DCF	-	Dispersion compensating fiber
DSF	-	Dispersion shifted fiber
DWDM	-	Dense wavelength division multiplexing system
DWFL	-	Dual-wavelength fiber laser
EDF	-	Erbium-doped fiber
EDFA	-	Erbium-doped fiber amplifier
EDFL	-	Erbium-doped fiber laser
ER	-	Extinction ratio
ESA	-	Electrical spectrum analyzer
FBG	-	Fiber bragg grating
FC/PC	-	Ferrule connector / physical contact
FC/APC	-	Ferrule connector / angled physical contact
FDTD	-	Finite difference time domain
FMF	-	Few mode fiber
FWM	-	Four wave mixing
FWMC	-	Four wave mixing cascades

HNLF	-	Highly nonlinear fiber
MFD	-	Mode field diameter
MWFL	-	Multiple wavelength fiber laser
LD	-	Laser diode
MMF	-	Multi-mode fiber
MZI	-	Mach-Zehnder interferometer
OFC	-	Optical frequency comb
OIL	-	Optical injection locking
OPLL	-	Optical phase locked loop
OPM	-	Optical power meter
OSA	-	Optical spectrum analyzer
OSNR	-	Optical signal to noise ratio
PD	-	Photodetector
PC	-	Polarization controller
PCF	-	Photonic crystal fiber
RF	-	Radio frequency
RFS	-	Recirculating frequency shifter
RoF	-	Radio-over-fiber
S-band	-	Short wavelength-band
SA	-	Saturable absorber
SBS	-	Stimulated Brillouin scattering
SLCM	-	Self lasing cavity modes
SMF	-	Single mode fiber
SMS	-	Single mode-Multi mode-Single mode
SRS	-	Stimulated Raman scattering
TBPF	-	Tunable bandpass filter
TDF	-	Thulium-doped fiber
TDFA	-	Thulium-doped fiber amplifier
TDFL	-	Thulium-doped fiber laser
TLS	-	Tunable laser source
TMSIF	-	Two mode step index fiber
WDM	-	Wavelength division multiplexing

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CHAPTER 1

INTRODUCTION

This chapter provides a brief of the research background as well as the problem statement and followed by the objectives of the research work. Subsequently, the scope of research along with the main contribution of research work are presented. Thesis outline is then elaborated as an overview of each chapter. Overall, this chapter has covered the first step of the research work before going further to the extensive theories and reviews of previous works as well as the simulation and experimental discussion.

1.1 Research background

In the modern age, the fourth generation (4G) communication technology with operating frequency below 2 GHz has now reaching maturity and will soon be replaced with the fifth generation (5G) system [1], [2]. The 5G telecommunication system is proposed in order to increase the demand for high-speed data [3]–[5]. In the emerging 5G technology, the majority of technology providers opt to demonstrate the system in 60 GHz region, but it has a concern of severe signal attenuation due to oxygen resonance in the atmosphere [1], [6], [7]. Alternatively, Ericsson and Samsung have tested their 5G smart-phone system in 10 GHz, 20 GHz, and 30 GHz region respectively [8]–[10]. The testing results are promising in terms of stability connection and network coverage [11]–[13]. In another development towards 5G, utilization of 100 GHz frequency band is potentially attractive due to the advantages of low atmospheric attenuation perspective and offering ultrawide bandwidth [14]–[17].

It is however a huge challenge to generate frequencies in 10 GHz, 20 GHz, 30 GHz and 100 GHz region using conventional electronics methods since it requires very complex circuitries. Thus incurring a high cost for the implementation of the electronic systems as it is prone to electromagnetic interference [2], [18], [19]. Protecting the circuitry from ambient electromagnetic noises is vital to ensure high quality output. This protection scheme however is very tricky and difficult, making the overall system complicated and expensive [20]. Therefore, there is high motivation to generate the microwave signal by photonic methods to overcome the electromagnetic interference issues and offer a much cheaper solution [21]. This is owing to the inherited advantages of optical fibers such as broad bandwidth, low loss and simple implementations [22], [23]. Through photonic methods, generation of the microwave signal can simply be realized using conventional optical heterodyning process [24]–[26].

In the photonic methods, the microwave signal is generated through the optical heterodyning process in a photodetector (PD), where the two optical waves at different wavelengths are beating each other [27]. The wavelength spacing of the two optical waves corresponds to the generated frequency [28]. Based on the previous reports, this heterodyning technique is proven successful to generate a microwave signal with the frequency of reaching the THz region [29], [30]. In addition to that, the microwave signal generated by the optical technique demonstrated a frequency deviation of 0.00077% and power fluctuation within ±0.49 dB [19], [31]. Thus, the optical based microwave signal has decent stability, showing promising potential to be commercialized as a carrier source for 5G applications.

There are four categories to generate the microwave signal via optical technique, which are Optical Injection locking (OIL) [32], [33], Optical Phase-Lock Loop (OPLL) [34], [35], external modulation [36], [37], and fiber lasers [38]–[42]. Among these techniques, the technique of fiber lasers offers simple design compared to others because of the avoidance of a high-quality microwave reference sources, thus reducing the system cost significantly. Moreover, if the system involves in many interconnections and conversion between electronics and optics, loss compensation should be seriously considered. Therefore, a multiple wavelength fiber laser is proposed to produce the microwave signal. Multiple wavelength can be realized using many methods which include stimulated Brillouin scattering (SBS) [43], four-wave mixing (FWM) [44], [45], and single mode-multimode-single mode (SMS) interferometer [46], [47].

The concept of generating the microwave signal by incorporating the multiple wavelength source is illustrated in Figure 1.1. The multiple wavelength source is then

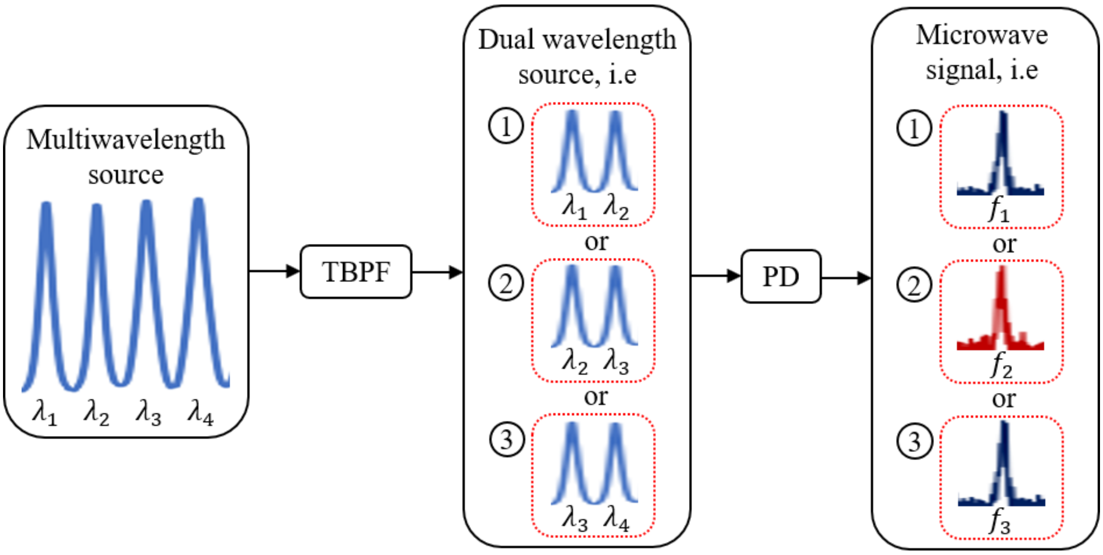

Figure 1.1: Application of the multiple wavelength fiber laser [38]

filtered by using tunable bandpass filter (TBPF). As a result, a different combination of two wavelengths are generated. When the two wavelengths beat with each other in the PD, a microwave signal with frequency equal to the wavelength spacing is generated. For instance, the wavelength spacing of 0.08 nm would generate approximately 10 GHz microwave signal. The photonics-based microwave generation offers a microwave signal with phase noise less than -60 dBc/Hz. This is due to the fact that the phase of the two wavelengths are correlated as it is generated from the same cavity. The microwave signal able to generate frequency range from 10 GHz to 100 GHz by tailoring the wavelength spacing of the two wavelengths [38], [39]. Improving the spacing between the two lasing components is thus essential to achieve the microwave source for 5G applications.

1.2 Problem statement

In order to elevate the performances of multiple wavelength sources, four main problems are identified in this research work. Out of four, two problems are related to multiple wavelength based on erbium doped fiber amplifier (EDFA). Another two related to multiple wavelength based on thulium doped fiber amplifier (TDFA).

The first problem based on EDFA is associated with unknown parameters value of the elements behind the generation of Stokes lines in multiple wavelength Brillouin erbium fiber laser (BEFL). In the previous work, the properties of erbium doped fiber (EDF) and stimulated Brillouin scattering (SBS) such as the optimum value of optical fiber length is not investigated yet [43], [48]–[52].

The second problem based on EDFA is related with limited number of comb lines in multiple wavelength four-wave mixing cascades (FWMC). Conventionally, the configurations of FWMC require optical modulators for SBS suppression [53]–[61]. Such requirements degrade the FWMC performance [62], [63]. Thus, a configurations of self-seeded FWMC are proposed. [64], [65]. In such configurations, only 10 comb lines are generated, illustrating the limited number of comb lines.

The third problem based on TDFA is associated with a fixed wavelength spacing of 0.08 nm (~10 GHz) in multiple wavelength Brillouin thulium fiber laser (BTFL). A cavity reconstruction is proposed to obtain double, and triple-Brillouin-frequency spacing (BFS) [66], [67]. In another designs, three Brillouin gain mediums (BGMs) are utilized for the generation of triple BFS [68], [69]. Both designs possess a concern of compactness.

The fourth problem based on TDFA is related with narrow wavelength spacing in multiple wavelength Thulium doped fiber laser (TDFL). It is known that the SBS and FWMC based method suffers from the lack of the wavelength spacing tunability [43]. Both methods require few amplifiers to tune the wavelength spacing [70]. The requirement increases the complexity of the system [44], [45], [71].

1.3 Research objectives

The main objective of this research is to elevate the current multiple wavelength generation performances that utilizes the gain medium of EDFA or TDFA in the operation. Specific objectives are as follow:

(i) To investigate numerically the properties and behaviour of EDFA and SBS effect in the multiple wavelength BEFL (MBEFL).

(ii) To optimize the number of comb lines in the multiple wavelength FWMC by varying the BP wavelength.

(iii) To design an adjustable Brillouin frequency spacing of multiple wavelength BTFL by incorporating a micro air gap

(iv) To enhance the wavelength spacing of multiple wavelength TDFL in which the mechanism of an SMS interferometer is applied.

1.4 Research scope

The scope of this research work which illustrate links between the four studies is shown in Figure 1.2. This research work is focused on multiple wavelength generation which exploits either EDFA or TDFA as their engine of operation. The EDFA operates in conventional-band (C-band) region range from 1530 nm to 1565 nm. Meanwhile, TDFA operates in short-band (S-band) region range from 1460 nm to 1530 nm whereas the EDFA could not cover such region. Based on the standard optical fiber performance, the lowest attenuation is in the region of C-band and S-band.

In EDFA, the research work is concentrated on cascaded FWM and fiber laser. The fiber lasers have the edge of being more robust against surrounding. It is known that BEFL stand out in the sense that having a low threshold power and a relatively high power when compared with BFL. In this research work, two studies are conducted on BEFL. The first study as highlighted as number 1 in Figure 1.2 is about a numerical analysis of signal recycling in MBEFL. This study is to address the first objective as stated in sub-chapter 1.3. In this study, a numerical analysis of EDFA and SBS effect is executed using MATLAB R2016b software.

Meanwhile, the second study as highlighted as number 2 in Figure 1.2 is about cascaded FWM seeded by a MBEFL. This study is conducted experimentally to achieve the second objective as stated in sub-chapter 1.3. In this study, the experimental setup of cascaded FWM is configured without optical modulator and analyzed at different BP wavelength.

Another technique to generate multiple wavelength is by utilizing TDFA. In TDFA, two types of fiber laser are concentrated which are BTFL and TDFL. As highlighted as number 3 in Figure 1.2, an experiment on BTFL with micro air gap cavity is realized to generate dual wavelength with single-, double-, and triple-Brillouin frequency spacing. The experiment is focused on the switchable operation in a bid to reduce the complexity of such design as addressed in the third objective in sub-chapter 1.3. A numerical calculation is then carried out using MATLAB R2016b software based on the dual wavelength experimental results to validate the concept of a switchable 10 GHz, 20 GHz, and 30 GHz region photonics-based microwave generation.

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