

Research on AWG-based Switching Dual-Wavelength Fiber Lasers

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Abstract. Compared with other lasers, fiber laser is widely used in optic communication, industrial production, biomedical sciences, and other fields because of its excellent technical performance, low manufacturing cost, mature technology, high conversion efficiency, high stability, and many other advantages. Recently, two new optical fiber communication techniques that are quickly evolving are Wavelength Division Multiplexing (WDM) and Dense Wavelength Division Multiplexing (DWDM). As a result, multiwavelength and wavelength-tunable fiber lasers were created to address the demand for optical communication systems with high throughput, high quality, and high speed. Due to their advantages in lowering equipment complexity, enhancing network flexibility, enhancing fiber system integration, etc., switching dual-wavelength fiber lasers based on Array Waveguide Grating (AWG) have received a lot of attention. This paper studies two switching dual-wavelength fiber laser based on AWG. Firstly, the basic structure of Erbium-doped Fiber Laser (EDFL) is analyzed based on the basic principle of Erbium-Doped Fiber (EDF). In addition, the working principle of AWG is analyzed emphatically. Finally, AWG-based switching dual-wavelength fiber lasers in linear/ring cavity, which achieve that the adjustable wavelength intervals between 0.8nm to 12nm, are verified and discussed experimentally. Additionally, experimental data shows that the dual-wavelength lasing power is stable and equal.

Keywords: Switching Dual-wavelength Fiber Laser; AWG; Erbium-doped Fiber.

1. Introduction

Since the 20th century, with the development and wide application of Internet technology, human beings' material and spiritual life has been enriched, and the diversity of information business and information life has also been rapidly developed. As a result, there are higher requirements for the amount and speed of information transmission. Since then, large capacity, high speed, low cost and good maintenance have become the long-term goals of communication technology development [1, 2].

The term "fiber laser" refers to a range of lasers that use fiber as the laser medium. In the mid-late 1960s, the effective method of reducing fiber loss was introduced by Charles Kao et al. [3-5]. Then, by the end of the 1970s, the manufacturing of low-loss optical fibers had become very stable [6, 7]. Since then, optical fiber communication technology has become the mainstream technology. In terms of communication history, optical communication technology is regarded as revolutionary.. With the rapid speed of development, human beings have entered the era of optical communication. In 1986, S. B. Poole, Mears et al., from the University of Southampton, UK, developed a low-loss EDF using an improved Method of Chemical Vapor Deposition (MCVD) [8]. Therefore, S. B. Poole, Mears et al. developed the world's first EDFL with tunable wavelength output [9]. Later, the research group continued to explore Erbium-doped Fiber Amplifier's excellent performance (EDFA) [9]. They made a great contribution to the development of the optical fiber communication industry. By the 1990s, in addition to the subscriber line, optical fiber transmission has completely replaced the traditional cable communication. Optical fiber became the main body of the telecommunications network.

Into the 21st century, the enthusiasm for fiber laser research continues to increase. With the research and development of the discovery of the fiber laser, fiber lasers have an indispensable role in promoting the development of modern optical communication technology. Q-switched [10], mode-locked [11], multiwavelength output [12-19], single longitudinal mode output [20] and other different

forms of fiber lasers are active in various research fields all over the world. Therefore, fiber laser in all aspects of the characteristics can be improved.

Fixed wavelength fiber lasers are no longer in line with the development requirements of modern communication systems, because modern communication systems pursue greater communication capacity and more advanced WDM optical network technology. Therefore, several different methods have emerged to achieve multiwavelength tunable output of fiber lasers in recent years. Nonlinear polarization rotation and twin-core EDF are used to create a switchable multiwavelength optic laser with a straightforward design and reliable performance by Lian et al. [12]. Chen et al. created a two-stage Lyot filter based on the nonlinear effect using two cascaded polarization-maintaining fibers and two polarization controllers to produce a comb spectrum. [13]. Thus multiwavelength output is realized. Han et al. proposed and demonstrated a tunable all-fiber comb filter through a Mach-Zehnder interferometer [14]. The filter is characterized by precise control of channel spacing [14]. A switchable multiwavelength EDFL based on randomly distributed feedback was proposed by Zhu et al. [15]. A semi-open laser cavity is created by using a circular mirror, and typical random laser radiation is produced [15]. A switchable multiwavelength optic laser with two elliptical structures as well as a core offset splicing junction was described by Chang et al. in a mixed-structure fiber filter [16]. Later on, the research group also made improvements to and suggested an adjustable multiwavelength optic laser based on a hybrid cascaded optic filter made up of one single ellipsoidal hybrid optic filter and a Sagnac ring interferometer [17]. So far, many comb filters, such as cascade Sagnac filter, birefringent filter, high order Loyt-Sagnac filter, and AWG filter, have been proposed to promote the development of multiwavelength tunable fiber lasers.

In this paper, two AWG-based switching dual-wavelength fiber lasers are proposed and experimentally demonstrated. One is a fiber optic laser with linear cavity, and the other is a fiber optic laser with ring cavity. Both of them used an AWG as a wavelength filter. Adjusted by optical switches in conjunction with the AWG, a range of 0.8-12 nm dual-wavelength lancing are obtained [18-20]. The coupler is used in the fiber laser to cause unbalanced loss in the two cavities. By placing a Variable Optical Attenuator (VOA) in the reduced loss cavity, the loss in the cavity is optimized. Consequently, it is achievable to achieve both a constant power level as well as dual wavelength lasing.. AWG has the advantages of small size, flexible design, low manufacturing cost and easy coupling to optical fibers. AWG also has a flat frequency response platform, less than 3dB insertion loss, and better than 35dB crosstalk level. AWG can be easily integrated with semiconductor optical amplifiers, photodetectors, light modulators and lasers. AWG is the ideal device in DWDM optical communication network, which greatly improves the reliability and reduces the size of optical fiber communication devices. Therefore, the switching dual-wavelength fiber laser based on AWG are beneficial to reduce the complexity of equipment, improving the flexibility of the network, enhancing the integration of the fiber system, etc.

2. Principle

2.1. Basic Principles of EDFL

2.1.1 Doped Fiber

The optical fiber usually uses glass as the substrate. The doped fiber is formed when rare earth ions are mixed into the fiber with a certain combination and concentration. In fact, the rare earth ions correspond to rare earth elements, which are the general name of 17 kinds of metal elements about lanthanide elements and scandium, yttrium. But accurately speaking, the doped fiber doped rare earth ions are selected from 15 kinds of lanthanide metal elements. Because these 15 lanthanides all have the same full shell structure, their optical properties are determined by the inner 4f electrons. A trivalent rare earth ion is formed when two 6s electrons and a 4f electron ionize. Due to the shielding effect of 4f electron on the external field, the external field has little influence on the optical absorption and fluorescence transition of rare earth ions.

As the substrate material of doped fiber is glass, glass is composed of covalent molecules and presents a chaotic network array structure. Therefore, rare earth ions such as Er^{3+} , Yb^{3+} , Tm^{3+} and Nd^{3+} can refract the wave and optical signal. Thus, rare earth ions can affect the nonlinear refractive index of the fiber. In other words, rare earth ions do the job of regulation and repair in the network structure. In addition, the optical properties of optical fibers are greatly influenced by rare earth ions.

When the doping concentration is moderate, the doped fiber will have nonlinear properties of conventional fiber. According to the current research shows that for the general silicon-based fiber, the doping concentration is generally in the range of hundreds to one thousand parts per million (ppm) is more appropriate [21].

2.1.2 The Spectral Characteristics of EDF

The energy level structure of Er^{3+} includes $^4\text{H}_{11/2}$, $^4\text{F}_{5/2}$, $^4\text{F}_{7/2}$, $^4\text{F}_{9/2}$, $^4\text{I}_{15/2}$, $^4\text{I}_{11/2}$, $^4\text{I}_{13/2}$ along with $^4\text{I}_{9/2}$. However, when the pump light source passes through the EDF, the Er^{3+} will be excited to different excited state energy levels by the action of different wavelengths of pumped light. When a pump light source with a wavelength of 980nm is used, Er^{3+} will form a classical three-level structure system, where level of $^4\text{I}_{11/2}$, $^4\text{I}_{13/2}$, as well as $^4\text{I}_{15/2}$ are the excited state, the metastable state, and the ground state, respectively. Among them, the pump wavelength required for $^4\text{I}_{15/2}$ excitation to $^4\text{I}_{11/2}$ and $^4\text{I}_{15/2}$ excitation to $^4\text{I}_{13/2}$ is 980nm and 1480nm respectively, while $^4\text{I}_{13/2}$ relaxation to $^4\text{I}_{15/2}$ will lose the light energy with wavelength of 1530nm by radiation, as shown in Fig. 1.

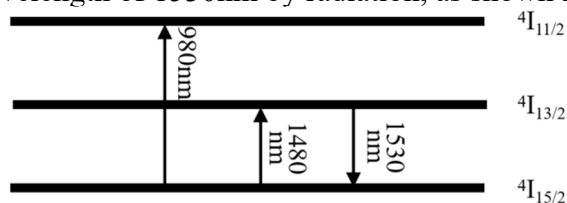


Fig. 1 Energy level transition of erbium ion

As shown in Fig. 2, level 1 is $^4\text{I}_{15/2}$ called the ground state. Levels 2 as well as 3 are represented by $^4\text{I}_{13/2}$ and $^4\text{I}_{11/2}$, respectively. W_{xy} ($x, y=1, 2, 3$) indicates that energy is transferred or lost in the form of radiation when energy level x transitions or relaxes to energy level y . A_{xy} ($x, y=1, 2, 3$) indicates that energy is transferred or lost in a non-radiative form when energy level x transitions or relaxes to energy level y . Therefore, as seen from Fig. 2, after absorbing the pump energy of 980nm, Er^{3+} will be excited from $^4\text{I}_{15/2}$ to $^4\text{I}_{11/2}$ in the form of radiation, and $^4\text{I}_{11/2}$ will also lose energy in the form of radiation, and then relax to $^4\text{I}_{15/2}$. Or, $^4\text{I}_{11/2}$ will relax non-radiatively to $^4\text{I}_{13/2}$, and subsequently, $^4\text{I}_{13/2}$ will relax to $^4\text{I}_{15/2}$ through a non-radiative or radiative manner. Among them, the ion lifetime of $^4\text{I}_{13/2}$ is about 10ms. Although only milliseconds, $^4\text{I}_{13/2}$ is already relatively long. In comparison, the ion lifetime of $^4\text{I}_{11/2}$ is very short, only about 1 microsecond.

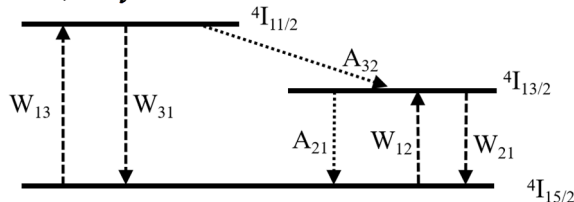


Fig. 2 The structure of erbium ion's energy level

The number of particles on the excited state is almost zero because they will quickly relax to the metastable state. The quantity of particles on the metastable state can swiftly build up since it takes much longer for particles on the metastable state to relax to the ground state. Therefore, the particle population inversion can be achieved at $^4\text{I}_{15/2}$ and $^4\text{I}_{13/2}$ of Er^{3+} . Then, under the excitation of Excited State Absorption (ESA) or light wave signals in the optical fiber, the high energy level of Er^{3+} will produce a large number of photons of the same state in the form of stimulated radiation. Finally, the photons will converge to form a laser. Therefore, in order to realize the laser output make, it is often necessary to choose a three-level system or even a four-level system to ensure that the particle number inversion of the laser gain medium can be achieved between some two levels.

2.1.3 The Basic Structure of Fiber Laser

The pump source, gain medium, along with optical resonator are the three main parts of a fiber laser. Photons can be produced by the gain medium. For optical feedback, optical resonators and pump sources are employed. The pump light energy from the coupler is absorbed by the gain medium. Thus the number of particles is reversed. Through the feedback and amplification of the optical resonator, the interaction between the light and the atom causes the stimulated radiation. Finally, the whole process of laser output is completed.

The pump source is a kind of external excitation source that can excite the particles from the low to the high energy level so that the gain medium can realize the reversal of the particle number. There are four main pumping modes of pump source: optical, electric, chemical, and pneumatic. Due to different doping elements, the optical cable produces different absorption bands and fluorescence bands for the doped fiber laser. Therefore, the pump wavelength also changes. Theoretically, the wavelength of the pump light should strictly be smaller than the fiber laser's maximum output wavelength. [22]. For example, using a pump source with a wavelength smaller than 1536nm for erbium-doped fiber can theoretically generate a laser of 1536nm [22].

The laser working medium is the key element in the manufacture of the laser, which can be in the form of gas, liquid, solid or semiconductor. Nonlinear fiber lasers use nonlinear properties such as stimulated Raman scattering and graphene as the most important measures to obtain laser. In contrast, induced radiation is the most important method to obtain laser by doping fiber laser.

The optical cavity generally comprises an optical lens and a laser crystal. At the same time, the optical cavity doped with the laser working medium is called an active cavity, and the optical cavity that the laser crystal is not incorporated into the laser working medium is called a passive cavity. Through the different cavity structure, the resonator can be divided into two categories: line cavity and ring cavity.

2.2. The Working Principle of AWG

AWG consists of input/output waveguide, input/output plate waveguide and array waveguide. The two plate waveguides, which connect the input/output waveguide and the array waveguide, adopt Loran circle structure to reduce the diffraction distortion. In order to introduce a constant phase difference, it is necessary to use adjacent array waveguides with a fixed length difference [5, 23]. Enough roots of array waveguide are needed to collect as much optical power as possible to ensure the quality of the output signal [5, 23]. Finally, due to the interference phenomena and output from several output waveguides, the optical signals with various wavelengths are concentrated at various locations of the output waveguide. At last, the demultiplexing function is realized.

Transmitting the optical signal in the array waveguide satisfies the grating equation. Since the input and output angles are small, the grating equation is as follows [23]:

$$\begin{aligned} n_s S \theta_{in} + n_a L + n_s D \theta_{out} &= m \lambda \\ \theta_{in} \approx \sin \theta_{in} \quad \theta_{out} \approx \sin \theta_{out} \end{aligned} \quad (1)$$

where the refractive indices of array waveguide and plate waveguide are n_a and n_s , respectively [23]. Waveguides in an array are spaced apart by S [23]. The distance in length L between consecutive array waveguides [23]. The m is the diffraction order of the grating [23]. The angle between the input waveguide and the plate's center axis is denoted by the symbol θ_{in} [23]. The angle at which the output waveguide and the plate's center axis meet is known as θ_{out} [23].

The group refractive index of the array waveguide is n_g that [23]:

$$n_g = n_a - \lambda \frac{dn_a}{d\lambda} \quad (2)$$

The dispersion equation for AWG can be obtained as [23]:

$$\frac{d\theta_{out}}{d\lambda} = \frac{mn_g}{n_s n_a S} \quad (3)$$

When designing an AWG, the first thing to do is to determine the number of AWG channels. However, the Free Spectral Range (FSR) determines the total output channel capability of the AWG. Therefore, it is very important to know the FSR of the AWG. The representation of FSR is:

$$FSR = \frac{c}{n_g(L+S\sin \theta_{in} + S\sin \theta_{out})} \quad (4)$$

3. Experimental Research of Switching Dual-wavelength Fiber Laser Based on AWG

3.1. Linear Cavity Structure

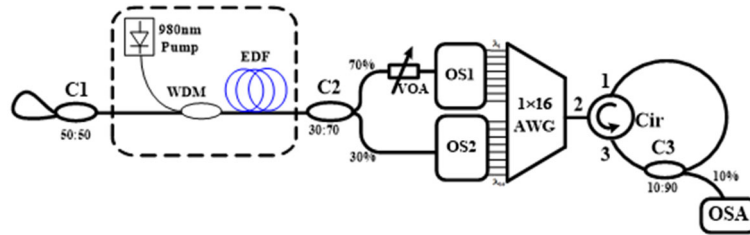


Fig. 3 Experimental device of linear switching dual-wavelength optic laser

Fig. 3 shows experimental apparatus of a switching dual-wavelength EDFL based on AWG [18]. A 980/1550 nm WDM, a pumping laser diode operating at 980nm with adjustable injection current, as well as a 5m-long EDF can make up an EDFA module [18]. A 1×16 AWG regulate every adjacent channel (CH1-CH16) with spacing as 0.8 nm [18]. What a 50:50 optocoupler (C1) dose is to make optical signal returns to the left cavity of fiber laser [18]. The Cir and C3 form a resonator. A set of 3-port ring actuators (Cir) ensures that the light is converted in a single direction within the resonator [18]. A 10:90 optical couplers (C3) acting as feedback forms a ring path for the photon waveguide [18]. Two 1×8 optical switches (OS1 and OS2) are used as band selectors [18]. A 30:70 optocoupler (C2) divides the linear cavity into two cavities with different cavity losses [18]. To make the powers of dual-wavelength in equal, a VOA is installed to reduce the difference in spectral gain characteristics in the two cavities [18]. With a resolution of 0.02/0.05nm, the Optical Spectrum Analyzer (OSA) is used to view and measure output results of fiber lasers. [18].

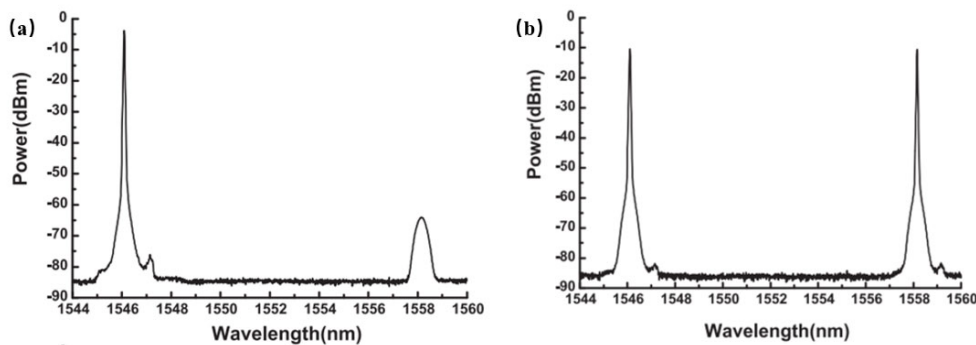


Fig. 4 (a)VOA=0, (b)Balance the output power

With a constant current of 300mA injected into the 980nm pumping laser diode, as shown in Fig. 4, the operation of the two wavelengths are converted by OS1 and OS2 to CH1 (1546.1nm) and CH16 (1558.16nm), respectively [18]. The cavity loss is not in a balanced state when VOA=0, the wavelength loss of CH16 (1558.16nm) is large, while the wavelength loss of CH1 (1546.1nm) is small. Therefore, the wavelength of CH1 is very obvious and the vibration is realized, while the wavelength of CH16 is too weak to achieve resonance. It presents an approximate state of single wavelength output. When adjusted to the corresponding VOA value, as shown in Fig. 5 [18], dual-wavelength output power can be regarded as balanced. It presents an state of dual-wavelength output.

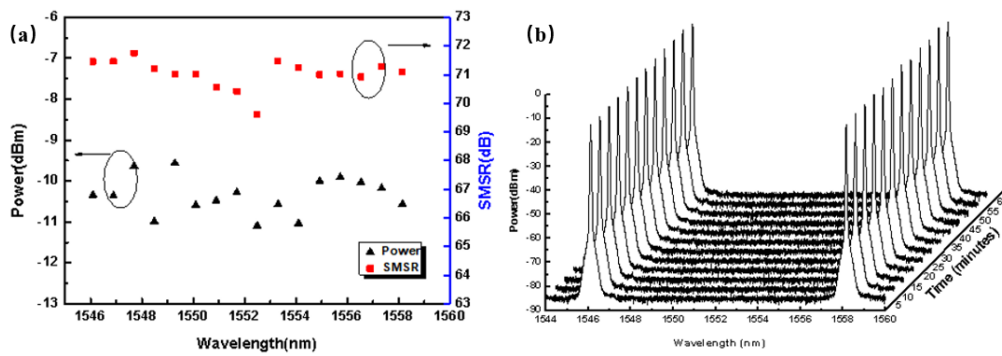


Fig. 5 (a)Wavelength peak power and SWSR, (b)Stability of CH1 and CH16

As shown in Fig. 5 [18], with dual wavelength output from CH1 and CH16, CH2 and CH15, etc., the largest channel-to-channel difference measured is 1.53 dBm, while the mean power of output for all 16 channels would be estimated to be roughly -10.35 dBm. [18]. All 16 channels have SMSRs that are higher than 69.5 dBm [18]. As seen in Fig. 9 [18], the performance of the chosen CH1 and CH16 pair is displayed at 5-minute intervals throughout the one-hour observation period when 300mA current is injected into a 980nm pumped laser diode. The maximum fluctuations of power and wavelength of CH1 and CH16 are 1.4dBm and 0.02nm, 1.88dBm and 0.012nm, respectively [18]. The switching dual-wavelength optical laser’s output has good and steady optical qualities, according to all the results.

3.2. Ring Cavity Structure

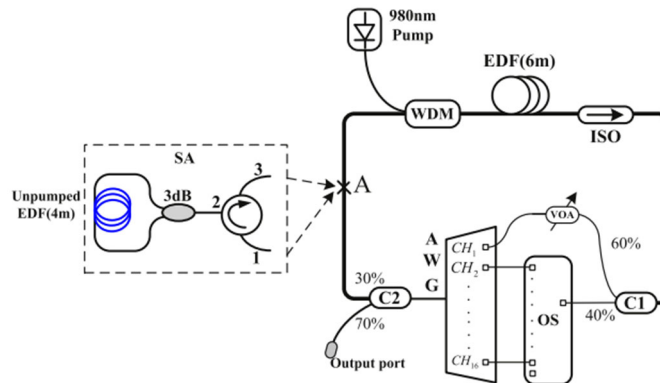


Fig. 6 Experimental device of switching dual-wavelength fiber laser in ring cavity structure

Fig. 6 shows another configuration of a switching dual-wavelength EDFL based on AWG, using a ring cavity [19]. The working principle is almost the same as that of linear switching dual-wavelength EDFL based on AWG. The two 1×8 optical switches in Fig. 3 are replaced by a 1×16 optic programming switch. The alteration ensures a single longitudinal mode and enhances double wavelength lasing by adding a saturable absorber based on a 4 m unpumped EDF into the main cavity [19]. Since the optical laser operates in single longitudinal mode, the self-injection feedback mechanism helps to reduce mode hopping and competition. In this configuration, by correctly adjusting the VOA placed in the lower loss cavity, different forms of single or dual wavelengths lasing can be chose.

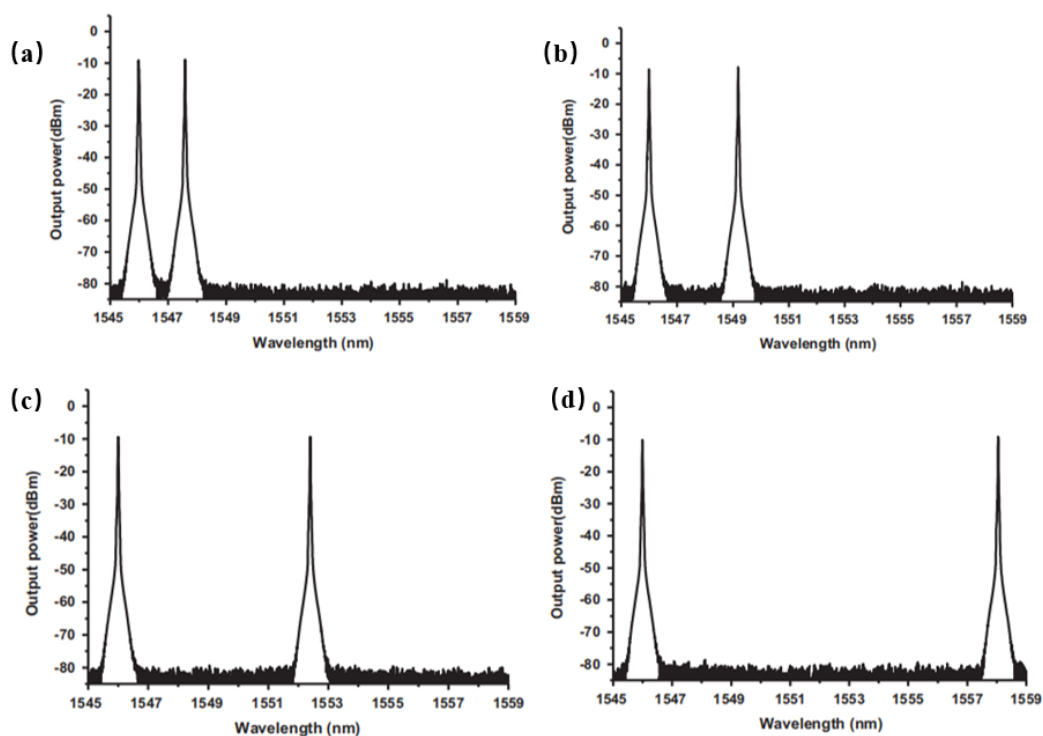


Fig. 7 Spacing of different output channels (ring cavity): (a)Wavelength spacing=1.6nm, (b)Wavelength spacing=3.2nm, (c)Wavelength spacing=6.4nm, (d)Wavelength spacing=12nm

Fig. 7 shows the dual-wavelength output with various widths from the ring fiber laser [19]. Dual-wavelength output with different distances can be achieved by properly attenuating VOA. Additionally, the average as well as consistency of all dual-wavelength output power tests is -10dBm [19]. SWSR readings for each of the 16 channels are higher than 68dB [19]. The article [19] states that the pump power must be restricted to a particular amount. The differential frequency signal makes it difficult to ensure the single-longitudinal mode when the pump power is more than 35mW [19].

4. Summary

The main aim of this thesis is to study and verify dual-wavelength fiber lasers with controlled wavelength switching. The content includes analyzing the structure and principle of EDFL, introducing the working principle of AWG, and setting up the experimental device according to the experimental principle under the existing laboratory conditions. Through an 1×16 AWG, the wavelength spacing can be adjusted by optical fiber switches between 0.8nm and 12nm. Inserting a VOA can balanced loss in both cavities. Finally, the test data analysis and comparison of both AWG-based switching dual-wavelength fiber lasers show that the SMSR is greater than 68dBm. Therefore, whether it is the linear cavity or the ring cavity, it can be confirmed that the switchable dual-wavelength optic laser has a certain optical characteristic and stability.

In recent years, with the wide application of DWDM, in order to break the limitations of data remote transmission and realize the upgrade of transmission speed and data carrying capacity, fiber lasers, especially the switchable fiber lasers suitable for DWDM systems, have set off a wide range of research upsurge. The main research content of this paper is switching dual-wavelength fiber laser, especially the switching dual-wavelength fiber laser based on AWG frequency selection and optical switching control. AWG has flat frequency response. Besides, AWG is small in size, low in cost, flexible in design, easy to couple with fiber, and easy to integrate with photodetectors, semiconductor optical amplifiers, optical modulators and lasers. Thus, the volume of optical fiber communication devices can be further reduced and the reliability of optical fiber communication devices can be improved. It is believed that it has certain research and application value.

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