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Permalink
https://escholarship.org/uc/item/5d03k1ts

Journal
IEEE Photonics Technology Letters, 26(2)

ISSN
1041-1135

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Publication Date
2014

DOI
10.1109/lpt.2013.2291834

Peer reviewed

Simultaneous Dual-Band Wavelength-Swept Fiber Laser Based on Active Mode Locking

Hwi Don Lee, Zhongping Chen, Myung Yung Jeong, and Chang-Seok Kim

Abstract—We report a simultaneous dual-band wavelength-swept laser based on the active mode locking method. By applying a single modulation signal, synchronized sweeping of two lasing-wavelengths is demonstrated without the use of a mechanical wavelength-selecting filter. Two free spectral ranges are independently controlled with a dual path-length configuration of a laser cavity. The static and dynamic performances of a dual-band wavelength-swept active mode locking fiber laser are characterized in both the time and wavelength regions. Two lasing wavelengths were swept simultaneously from 1263.0 to 1333.3 nm for the 1310 nm band and from 1493 to 1563.3 nm for the 1550 nm band. The application of a dual-band wavelength-swept fiber laser was also demonstrated with a dual-band optical coherence tomography imaging system.

Index Terms—Fiber lasers, laser mode locking, optical imaging.

I. INTRODUCTION

OVER the last decade, wavelength-swept lasers have been widely investigated for various sensing and imaging applications [1]–[6]. Conventional wavelength-swept lasers consist of a wide-band gain medium and a wavelength-selecting filter in the cavity. The sweeping mechanism of a wavelength-swept laser is determined mainly by the mechanical-tuning property of the filter, such as a fiber Fabry-Perot tunable filter (FFP-TF) [2], [3] and a polygon mirror-scanning filter [4]. Recently, we reported on a novel filter-less wavelength-swept laser based on active mode locking (AML) and showed the feasibility of producing an OCT image [5]. *In-vivo* OCT imaging was also reported based on this AML wavelength-swept laser [6]. Because there is no mechanical wavelength-tunable filter, the mechanical limitation on their imaging performance can be successfully eliminated [5].

Specially, dual-wavelength lasers have been widely developed for differential absorption light detection and ranging (LIDAR) [7], [8], microwave generation [9], [10]

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Digital Object Identifier 10.1109/LPT.2013.2291834

and spectroscopic dual-band OCT imaging [11]–[13]. Many different kinds of dual-band lasers have been proposed, but most of their schemes consist of two gain regions and a wavelength-selecting filter in the laser cavity [11]–[13]. For example, in the case of a dual-band wavelength-swept FDML fiber laser, the FFP-TF is inserted into the cavity to sweep each wavelength-band [11], [12]. It is not easy to tune a dual channel driver for the two FFP-TFs for simultaneous oscillation in the ring cavities of both bands [11]. In the case of a dual-band wavelength-swept source based on a polygon mirror scanning filter, two narrowband intra-cavity wavelength filters with a single high-speed polygonal scanner have been used [13]. However, these mechanical filter causes disadvantages, such as high cost, limited stability and bulk volume, needed to tune the center wavelength.

In this letter, we describe novel type of simultaneous 1310 and 1550 nm-bands wavelength-swept fiber lasers based on the AML method. The principle of dual-wavelength lasing and simultaneous tuning is theoretically analyzed, and the experimental characteristics of a dual-band wavelength-swept AML fiber laser is presented in both the time-domain and wavelength-domain. A single modulation signal is applied to sweep both 1310 and 1550 nm-bands without a mechanical wavelength-selecting filter. Furthermore, we report simultaneous dual-band OCT imaging results using this novel swept source (SS) laser.

II. PRINCIPLE OF DUAL-WAVELENGTH TUNING BASED ON AML

In a harmonic mode locking condition in a fiber laser cavity, the lasing wavelength, λ_m of a stable short pulse train can be determined by modulating the injection current into the gain with a radio frequency (RF) signal at frequency, f_m, that is an integer (N) times the free spectral range (FSR); i.e. $f_m = N \cdot FSR$. The basis FSR, FSR_0, is simply given by the cavity length and the speed of light in the fiber cavity where $FSR_0 = c/nL$. However, in a chromatic dispersive medium, the FSR becomes a function of wavelength. This means that the lasing wavelength can be determined simply, as described in [5]

$$\lambda_m = \lambda_0 - S \cdot (f_m - f_{m0}) \tag{1}$$

where λ_0 is the basis output wavelength at a basis RF frequency of f_{m0}, and S is a sensitivity parameter given by

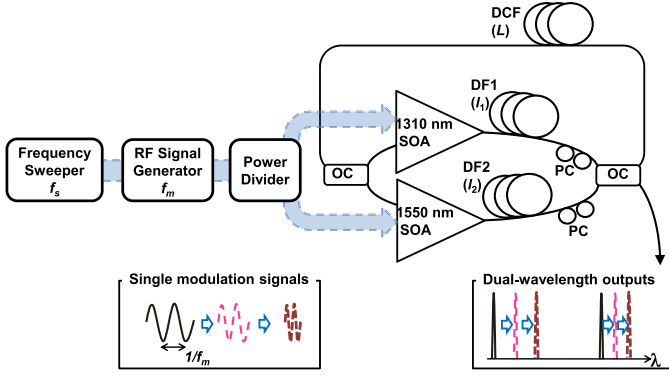$$S = \frac{n^2 L}{c^2 D N} \tag{2}$$

Fig. 1. Configuration of dual-band wavelength-swept active mode locking laser. (SOA: semiconductor optical amplifier, DCF: dispersion compensation fiber, DF: delay fiber, PC: polarization controller, OC: optical coupler).
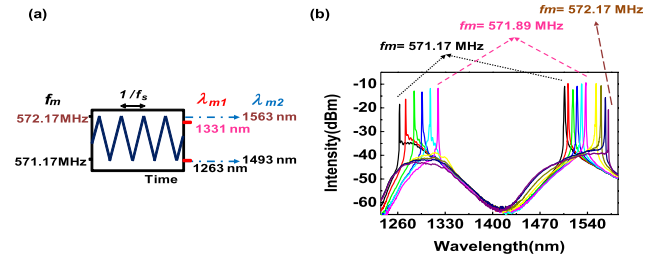

Fig. 2. (a) Concept of modulation frequency and repetition rate of dual-band wavelength–swept laser. (b) Static output spectra of the dual-band wavelength-swept AML laser for various modulation frequencies.

where n is the refractive index of the fiber at λ, L is the cavity length, c is the velocity of light in a vacuum, D is a dispersion parameter, and N is an integer of the mode-locking order.

From Eq. (1) and (2), we note that the difference between the lasing wavelength (λ_m) and basis wavelength (λ_0) is proportional to the difference between the modulation frequency of the RF signal (f_m) and the basis RF frequency (f_{m0}) by a factor of sensitivity parameter, S. Based on this principle of shifting wavelength via RF signal modulation, it is possible to expand the tuning of a single lasing wavelength into the tuning of multiple lasing wavelengths. For example as shown in Fig. 1, when we add two different delay path-lengths, l_1 and l_2, into the original path-length of L (such as $L + l_1$ and $L + l_2$), these two path-lengths can easily define two basis FSR values, FSR_{01} and FSR_{02}. Then the two corresponding basis RF frequencies of f_{m01} and f_{m02} can be expressed, respectively, by the following equations;

$$f_{m01} = N \cdot FSR_{m01} = N \cdot \frac{c}{n(L + l_1)}, \tag{3}$$

$$f_{m02} = N \cdot FSR_{m02} = N \cdot \frac{c}{n(L + l_2)}, \tag{4}$$

By substituting Eq (3) and (4) to Eq (1) can be expressed as

$$\lambda_{m1} = \lambda_0 - S \cdot \left(f_m - N \cdot \frac{c}{n(L + l_1)} \right), \tag{5}$$

$$\lambda_{m2} = \lambda_0 - S \cdot \left(f_m - N \cdot \frac{c}{n(L + l_2)} \right), \tag{6}$$

From Eq. (5) and (6), we expect that dual-wavelength outputs of λ_{m1} and λ_{m2} can be generated by a single modulation signal with a frequency of f_m. The separation of dual wavelength positions is determined from basis RF frequencies, f_{m01} and f_{m02}. By changing the modulation frequency, the dual-wavelength outputs can be swept simultaneously. As the modulation frequency is changed repeatedly, the sweeping of dual-wavelength outputs are be repeated accordingly. More than two wavelength outputs can be available by adding more than two delay path-lengths.

III. EXPERIMENTAL SETUP AND CHARACTERISTICS

A. Design of Dual-Band Wavelength-Swept AML Fiber Laser

Figure 1 shows the experimental set-up of the dual-band wavelength-swept AML fiber laser. The cavity consists of two semiconductor optical amplifiers (SOAs) for gain media, a polarization controller (PC), a dispersion compensation fiber (DCF) of length L for the high dispersive cavity, and two broadband 50:50 optical couplers (OCs). To demonstrate the dual-band wavelength-swept laser, two broadband SOAs with center wavelengths of 1310nm (ISPAD-1301, Inphenix) and 1550nm (ISPAD-1501, Inphenix), respectively, were used as gain media. The two SOAs at the 1310 nm band (O-band) and 1550 nm band (C-band) used in this experiment can reach a 3 dB bandwidth of 45 nm when currents of 250 and 350 mA, respectively, are applied. We inserted two different delay paths, l_1 and l_2, for these two SOAs for the dual-wavelength tuning of λ_{m1} and λ_{m2}, due to the two basis FSR values, FSR_{01} and FSR_{02}, and the two basis RF frequencies, f_{m01} and f_{m02}, respectively. It is important to select two broadband OCs to share a common path of the cavity for both the 1310 and 1550nm optical sources without insertion loss for the broad bands. PCs were used to adjust the polarization states. The dispersion coefficient, D, of the DCF is -80 ps/nm/km at 1310 nm and -90 ps/nm/km at 1550 nm. The total cavity lengths of $L+l_1$ and $L+l_2$ are $\sim$75 m and $\sim$76 m, respectively.

B. Other Recommendations

As we already have been shown in our previous study [5], there are some trade-off between instantaneous linewidth and overall bandwidth according to the mode-locking order (N). Therefore, the appropriated modulation frequency (f_{m0}) has been chosen for around 570 MHz regions by the optimal selection for OCT imaging. Figure 2 shows the static output spectra of the dual-band wavelength-swept AML laser in the modulation frequency, f_m, around the 570 MHz region. As the f_m was changed from 571.17 to 571.89 MHz, the lasing wavelength at the 1310 nm band, λ_{m1}, shifted from 1263.0 to 1333.3 nm, respectively. As f_m was changed from 571.17 to 572.17 MHz, the lasing wavelength at the 1550 nm band, λ_{m2}, shifted from 1493.0 to 1563.3 nm, respectively. During 571.89 MHz to 572.17 MHz, 1310 nm band is not lasing because of limited gain bandwidth of SOA. A tuning range of 70.3 for the 1310 nm band and 70 nm for the 1550 nm band
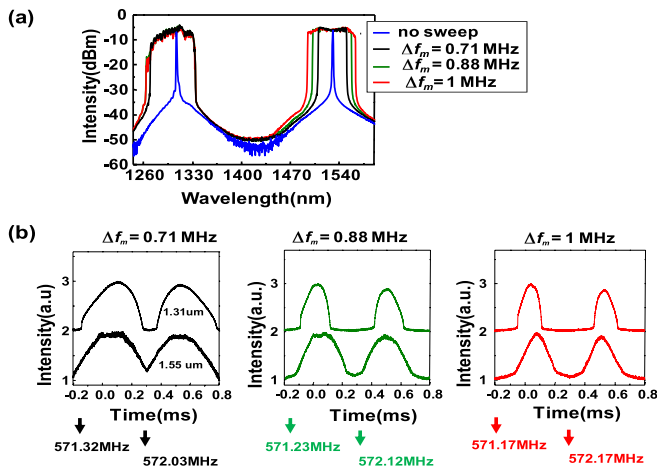
Fig. 3. (a) OSA peak-hold mode spectra. (b) Time domain tracing of the dual-band wavelength-swept AML laser output.
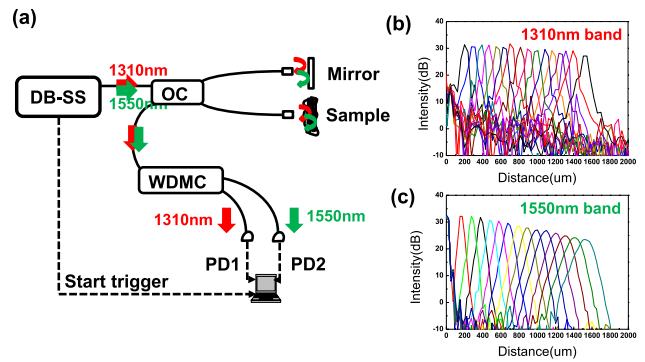

Fig. 4. (a) Schematic diagram of our dual-band swept-source OCT system (DB-SS: dual-band swept-source, OC: optical coupler, WDMC: wavelength-division-multiplexing coupler, PD: photo detector). (b), (c) Point spread function of the 1310 nm band and 1550 nm band outputs, respectively.

was obtained. The total bandwidth of the wavelength-swept AML laser can be determined simultaneously from the tuning range of FSR and the gain range of SOA. From the experiment, the sensitivity parameter, S, shows different tuning sensitivities of 97.6 nm/MHz for the 1310 nm band and 70.0 nm/MHz for the 1550 nm band because the tuning sensitivity depends on the dispersion coefficient, mode-locking order (N) and FSR at two different wavelength bands. The 3 dB linewidth of the lasing peak was measured to be 0.69 nm at 1308 nm and 0.78 nm at 1553 nm. According to mode-locking theory, the linewidth can be further reduced through optimal use of the controlling dispersion parameter and mode-locking order [5]. The measured optical output powers are 600 μW and 550 μW for 1310nm and 1550nm bands, respectively.

To sweep the wavelength dynamically, we used an external frequency sweeper to generate a triangular signal as a frequency modulation (FM) function. The frequency of this FM function means the repetition rate, f_s, of the dual-band wavelength-swept AML laser source. The repetition rate and tuning range are easily controlled using the FM function.

Figure 3 (a) shows peak-hold mode spectra (detected using an optical spectrum analyzer) of the dual-band wavelength-swept laser output at a 1 kHz sweep rate for Δf_m value of 0.71 MHz, 0.88 MHz, and 1 MHz. Figure 3 (b) shows time tracking spectra at each Δf_m. Because the tuning sensitivity is higher at the 1310 nm band than at the 1550 nm band, the operation condition can be analyzed for full range tuning of both the 1310 and 1550 nm bands. For example, when Δf_m is 0.71 MHz and 0.88 MHz, as shown in Figs. 3 (a) and (b), the 1550 nm band is not fully tuned, but the 1310 nm band is under full range operation. Therefore, the condition of $\Delta f_m = 1$ MHz is selected for the full-range tuning. For this experiment, a perfectly synchronized dual-band wavelength-swept laser was easily obtained due to simple operation using the single modulation signal. In addition, because the final output of the dual-band laser source comes out from a single output port, it is not necessary to employ additional effort to combine two beams of dual bands into one position [11], [13].

As we reported previously [5], at the high repetition rate, the instantaneous linewidth become broader due to the respectively long cavity length of DCF cavity media. Even at the higher repetition rate above 700 kHz, the laser cannot sweep for the broad wavelength ranges because this value of repetition rate meets the half of FSR [5]. In this letter, therefore, a slower repetition rate (f_s) of 1 kHz has been chosen for optimal operation of reliable OCT imaging. However, we expect this disadvantage at high repetition rate can be easily overcome using a high-dispersion and short length medium such as chirped fiber Bragg grating (CFBG) [14]. The conventional DCF -used in this experiment- was not optimized for the shorter length and higher dispersion parameter, but it still has the advantage of a broad dispersive spectrum with which to apply the dispersion effect for the 1310 and 1550 nm bands simultaneously.

C. Optical Coherence Tomography Based on Dual-Band Wavelength-Swept AML Fiber

Figure 4 (a) shows the experimental setup of the dual-band SS-OCT system. The swept-source OCT system is basically a Michelson interferometer composed of a broadband 70/30 fiber OC. Because the dual-band output comes from a single output port, there is no need to make an additional sample arm (or probe) to expose two beams (both 1310 and 1550 nm bands) into the common sample simultaneously, unlike the other dual-band SS-OCT system [10], [12]. Therefore, after inducing most of the optical interference signals, the final stage of the optical signals are simply divided using a wavelength division multiplexing coupler (WDMC) and detected by two photo-detectors (1817-FC, New Focus) simultaneously. For a stable mode-locking condition, the wavelength-sweeping was operated at 1 kHz for axial direction tomography imaging. Figure 4 (b) and (c) show the measured point spread function (PSF) under various path length difference conditions. The signal-to-noise ratio (SNR) of the system at a position of ~200 μm from the path-matched depth was measured to be 38.3 and 42.09 dB for the 1310 and 1550 nm bands, respectively. Due to each integrated bandwidth of ~70.3 and 70.0 nm for this dual-band wavelength-swept AML laser source, the theoretical axial resolutions were
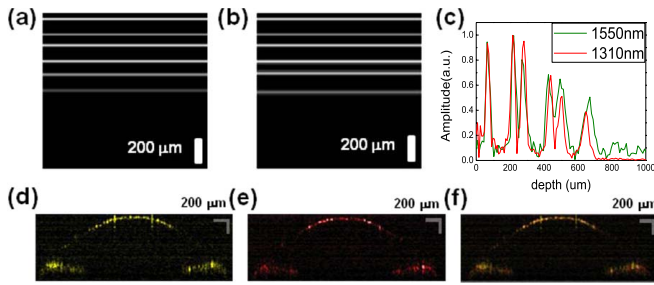
Fig. 5. (a) OCT image of three cover glasses using 1310 nm and (b) OCT image of three cover glasses using 1550 nm. (c) 1-D depth profiles of the three cover glasses. OCT image of a fish eye using (d) 1310 nm, (e) 1550 nm and (f) combined 1310/1550 nm.

calculated to be 10.7 and 15.1 μm for the 1310 and 1550 nm bands, respectively. The measured axial resolutions were 22.8 μm and 27.8 μm for 1310 and 1550 nm bands, respectively. Because the axial resolution is proportional to the square of the center wavelength, the 1310nm band shows better resolution. Furthermore, the linewidth of the lasing peak is related to the mode-locking order (N) and the dispersion coefficient (D) [5]. To obtain a similar mode-locking order N, the linewidth can be mainly determined using the dispersion coefficient D. Because the measured linewidth at the 1310 nm band is relatively narrower than that of the 1550 nm band, we note that the PSF sensitivity of the 1310 nm band dropped more slowly than that of the 1550 nm band.

Using the proposed dual-band wavelength-swept AML laser, various samples of cover glasses and fish eyes were prepared to compare 2-D OCT images according to both spectral regions. In the organic sample, a reduced OCT penetration depth is observed at the 1550 nm compared with 1310 nm because of the effect of water absorption. However in case of inorganic sample with low water content, the 1550 nm system exhibited better penetration [15]. As shown in Figs. 5(a) and (b), each layer of the three cover glasses can be distinguished clearly in both the 1310 and 1550 nm bands and the last layer is more clear at the 1550 nm band. Figure 5 (c) shows 1-D depth profiles of the three cover glasses from the OCT cross sections. Figure 5 (d)-(f) show OCT images of a fish eye measured by 1310 nm band light, 1550 nm band light, and 1310/1550 combined light, respectively. The Fig. 5 (f) was obtained after post-processing. Before combining two images, the both images are rescaled by using reference depth information such as mirror positions. After post-processing, we can rearrange both images in the same position and scale. Because of the high water content, we can monitor that the deeper image of 1310 nm band is relatively clearer than that of 1550 nm band. Because the spectral features of the different samples appeared at different wavelength bands, the optimized dual-band wavelength-swept laser will enhance the imaging contrast due to its spectral characteristics.

For a practical SS-OCT system using the proposed dual band wavelength-swept AML fiber laser, we are modifying it for the deeper imaging, higher resolution and a higher sweeping rate because the narrower linewidth, broader bandwidth and larger FSR, respectively, can be implemented by proper design of the laser cavity with a shorter length and higher dispersion medium in the laser cavity.

IV. Conclusion

A novel simultaneous dual-band wavelength-swept laser source was developed based on the active mode locking method. According to the dual FSR configuration of the dispersive laser cavity including two delayed path-lengths, we generated two synchronized lasing outputs at the 1310 and 1550 nm bands by applying a single modulation signal. The feasibility of the proposed dual-band wavelength-swept laser source for dual-band SS-OCT imaging was demonstrated using two kinds of transparent samples. Although current report focuses on the dual wavelength at 1310 nm and 1550 nm, the principle and design report in this letter can be extend to other dual wavelength regions for measurement of biological important parameters such as oxygen saturation for 800 nm band.

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