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A stable wavelength-spacing-tunable dual-wavelength single-longitudinal-mode fiber ring laser based on a DMD filter

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Abstract: A stable single-longitudinal-mode dual-wavelength (SLM-DW) multiple ring fiber laser with a tunable wavelength spacing was proposed and demonstrated. In the multiple ring cavities, the mode selection is made by the tunable digital micro-mirror device (DMD) filter and two different length passive sub-ring cavities. The DMD filter can select and couple any two wavelengths from the gain spectrum of the erbium-doped fiber (EDF). The SLM lasing is guaranteed by the two sub-ring cavities which serve as a mode filter. The stable and uniform dual-wavelength oscillation is obtained by the highly-nonlinear photonic crystal fiber (HN-PCF), which can generate the four-wave-mixing (FWM) effective. By loading different gratings on the DMD filter without any mechanically shift, the tunable wavelength spacing from appropriately 0.165 nm to 1.08 nm within a tuning accuracy of 0.055 nm is achieved at room temperature.

Key words: digital micro-mirror device, four-wave-mixing effective, single-longitudinal-mode
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基于 DMD 滤波器的波长间隔可调谐的双波长单纵模光纤环形激光器

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摘要:提出一种稳定的波长间隔可调谐的双波长单纵模环形光纤激光器.在复合环形谐振腔中,采用由数字微镜装置(DMD)滤波器和两个不同长度的次级环形谐振腔组成的多重滤波的方式来选择激光器的工作模式.其中,DMD 滤波器可以从掺铒光纤的自发增益谱中任意选择两个波长并将它们耦合进光路中;次级环形谐振腔作为模式滤波器,可以保证激光器输出单纵模激射;利用非线性光子晶体光纤(HN-PCF)的四波混频(FWM)效应,使激光器输出均衡平稳的双波长激射.在室温条件下,不用移动实验装置中的任何器件,通过将位置不同的光栅映射在 DMD 滤波器上来实现双波长间隔可调谐,调谐范围为 0.165 nm 到 1.08 nm,调谐步长为 0.055 nm.

关 键 词:数字微镜装置滤波器;四波混频效应;单纵模

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Introduction

In recent years, single-longitudinal-mode dual-wavelength fiber laser has been investigated intensively because of its potential applications in optical generation of microwave signal, wavelength-division-multiplexing (WDM), optical fiber sensors and optical instrument testing[1-3]. Compared with other lasers, erbium-doped fiber ring laser (EDFRL) has many competitive advantages, such as flexible experimental structure, low intensity noise, long life pumping and narrow output linewidth. To realize a stable and uniform SLM-DW lasing in EDFRL, however, we need to overcome two problems. On the one hand, because of long cavity length, fiber ring laser usually oscillates in multi-longitudinal-modes (MLM) and has very narrow longitudinal mode spacing, which are not conductive to the output of SLM lasing. On the other hand, the EDF is employed as the gain medium in the EDFRL. It has a server homogeneous line broadening effect at room temperature, which leads to the selected dual-wavelength lasing unstable and non-uniform.

In this paper, a stable SLM-DW erbium-doped fiber ring laser (SLM-DW-EDFRL) has been demonstrated to generate wavelength-spacing-tunable and stable SLM-DW lasing by incorporating a DMD filter[4-8], two sub-ring cavities[9] and a length of HN-PCF[10-12]. The unique feature and innovative point of this paper is that by utilizing a DMD filter, tunable dual-wavelength signal can be generated only through producing reconfigurable diffraction gratings to steer lasing wavelengths by means of the DMD filter without any mechanically shift. In the fiber ring cavity, the DMD filter can not only select and couple any two wavelengths from the amplified spontaneous emission (ASE) spectrum of an EDFA into the main fiber ring, but also route laser back into the corresponding fiber ring to generate signals. The FWM effect in HN-PCF can not only alleviate the mode competition, but also effectively suppress homogeneous line-broadening effect. Consequently, the highly-nonlinear PCF is employed for the generation of the four-wave mixing (FWM) to obtain stable and uniform dual-wavelength oscillation. Two different short passive sub-ring cavities, which are inserted into the main ring cavity and serve as mode filters, make SLM lasing. The two lasing wavelengths are easily electronically selected by loading different grating on the DMD filter via controlling the computer software. Based on the theoretical analysis and the experimental studies, the good performance of SLM-DW lasing can be achieved.

1 Experimental setup and principle

The schematic layout of the proposed experimental system for generating the SLM-DW lasing signals is showed in Fig. 1. The experimental setup is composed of an EDFA, a DMD filter, two sections of different lengths of single-mode optical fiber, a 30-m-long HN-PCF and a 1 200 mm^{-1} blazed grating plate. The erbium-doped fiber of EDFA (KEOPSYS) is employed as the gain medium. The DMD filter consists of 1024 × 768 pixel controlled by a micro electro mechanical element, any two wavelengths of the ASE spectra can be steered by uploading the corresponding voltage on the appropriate mirrors. Actually, the DMD filter is a two-dimensional blazed grating and its diffraction effect is very obvious in the near infrared band. The HN-PCF, which is inserted into the main fiber ring, has a nonlinear coefficient of ~ 11 W^{-1} km^{-1} and a flat dispersion of ~1 ps/nm/km around 1 550 nm. The two 2 ×2 optical couplers are connect to the single-mode optical fiber which have different length, and constitute the sub-ring cavity. The 1200 mm^{-1} blazed grating plate, which has 1 200 lines, is employed to demultiplex the ASE spectrum and generate astigmatism windows onto the surface of DMD filter. The polarization controller (PC) is employed to adjust and ensure the SLM oscillation, and also optimize the diffraction efficiency of the DMD filter for the purpose of maximizing by the use of aligning the ASE polarization. The function of collimator array is changing the divergent beam in the fiber into collimated light, so that they can take very little loss coupled into the optical fiber. The output power is split into two parts by a 10:90 1 ×2 optical coupler, 90% of output power is re-circulated in the main fiber ring while the 10% part is monitored by an optical spectrum analyzer (OSA). During the experiment, the PC is adjusted for the single longitudinal mode results. The whole process of generating DW-SLM signals is described below.

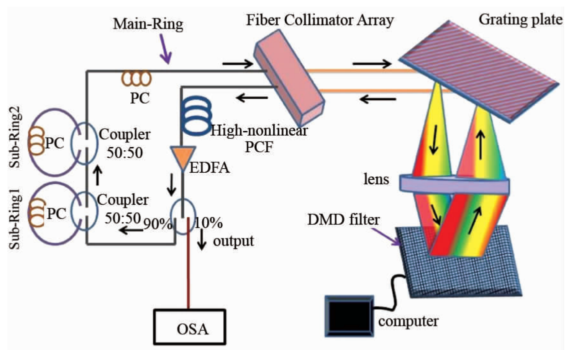

Fig. 1 Experimental setup. DMD: digital micro-mirror devices; PC: polarization controller; OSA: Optical spectrum analyzer.
图 1 实验装置图. DMD:数字微镜装置;PC:偏振控制器;OSA:光频谱分析仪

The DMD filter is used to generate reconfigurable diffraction grating to steer lasing wavelength in the proposed experimental system. By applying two different appropriate steering gratings onto the DMD filter without any mechanically shift, the arbitrary two lasing wavelengths can be independently and reliably steered and coupled into the fiber collimator. The mode competition caused by the EDF as a homogeneous medium is detrimental to the output of uniform dual-wavelength. In order to make the two beams lasing stable and uniform, the HN-PCF, which causes two degenerate FWM processes, is inserted into the main cavity. The basic principle of inhibiting mode competition by FWM is to compensate the optical power of different wavelength through the redistribution of beam energies[10]. Under the action of two degenerate FWM, the two beams lasing become stability and uniformly at room temperature.

However, the two selected wavelengths are MLM including many modes because of long cavity length and very narrow longitudinal mode spacing. In order to obtain DW-SLM, two passive sub-rings, which are referred to as a SLM filter, are employed to restrain the mode competition. In principle, each ring resonator has its own resonant frequency. For this reason, in the proposed system, the mode of two beams should fulfill the resonant conditions of both the main ring cavity and two sub-ring cavities concurrently in accordance with the Vernier Effect[13]:

$$FSR_{MRC} = 2mFSR_{main} = (2n+1)FSR_{sub} = (FSR_{main}, FSR_{sub1}, FSR_{sub2})_{LCM} \quad , \quad (1)$$

where FSR_{main} and FSR_{sub} denote free spectral ranges (FSRs) of main ring cavity and sub-ring cavity, respectively, FSR_{MRC} stands for the FSR of the multiple-ring cavity (MRC) and takes the least common multiple (LCM) of FSR_{main} with FSR_{sub}. Ultimately, the FSR_{MRC} gets a great value enough to restrain the mode competition, and the SLM dual-wavelength EDFRL can be achieved.

2 Experimental results and discussion

In the experimental setup, the wavelength changed 0.055 nm while one pixel shift (i. e., 0.055 nm/pixel) via operating computer software. At this point, we naturally extrapolate the DMD filter bandwidth to 0.055 nm, and the corresponding frequency bandwidth at 1550 nm can achieve 6.87 GHz. In order to obtain DW-SLM lasing, two sub-ring cavities are inserted into the main cavity. Due to the total length of main ring is about 42.4 m, including the highly-nonlinear PCF length of 30 m, FSR_{Main} is only 4.808 MHz, which is much less than the DMD filter bandwidth. However, when the main cavity is combined with two sub-ring cavities, mode competition will be suppressed well. The lengths of sub-rings are 1.9 m and 2.1 m, corresponding to the FSR of nearly 107.56 MHz and 97.31 MHz, respectively. According to Vernier Effect, the FSR_{MRC} can be reached more than 41.5 GHz, which is greater than the filter bandwidth. In this way, DW-SLM lasing can be reached. The procedure of controlling dual-wavelength spacing just need adjust DMD filter through computer software without any mechanically shift, which is not conducive to the stability of the wavelength spacing. The correspondence between wavelength spacing (nm) and wavelength spacing (pixel) is shown in Fig. 2.

Due to the function of DMD filter and two sub-ring cavities, the SLM lasing can be reached at room temperature. In order to verify this, optical heterodyning technique is used to generate microwave signals. The important prerequisite of using this technique is that the dual-wavelength lasing must be oscillating SLM. By applying the dual-wavelength lasing to a high-speed 30-GHz PD (u2t photonics The Optilab PD-30 GHz) before two sub-ring cavities are inserted into the main ring, as shown in the Fig. 3(a), no microwave signal can be seen from the ESA (R&S FSV-30 GHz). It illustrates that the dual-

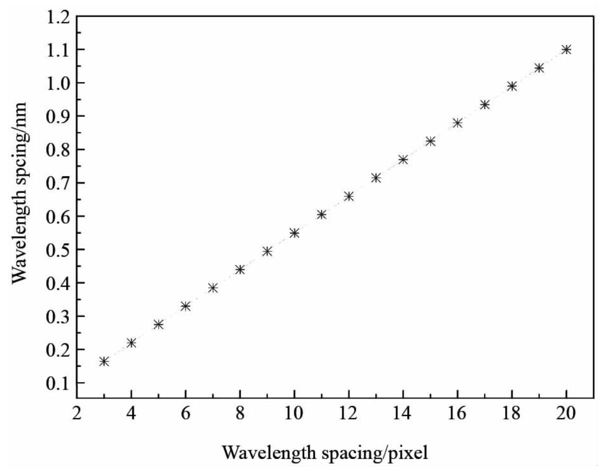

Fig. 2　Wavelength spacing (nm) vs wavelength spacing (pixel)
图 2　波长间隔(nm)vs 波长间隔(像素)

wavelength is oscillated in multi-longitudinal-modes (MLM). However, after the two sub-ring cavities were connected to the laser and the laser output was applied to the PD, a beat signal can be detected. Figure 3(b) shows that a ~27.47 GHz (when wavelength spacing is 4 pixels) microwave signal can be observed from ESA. It means the dual-wavelength operating in SLM.

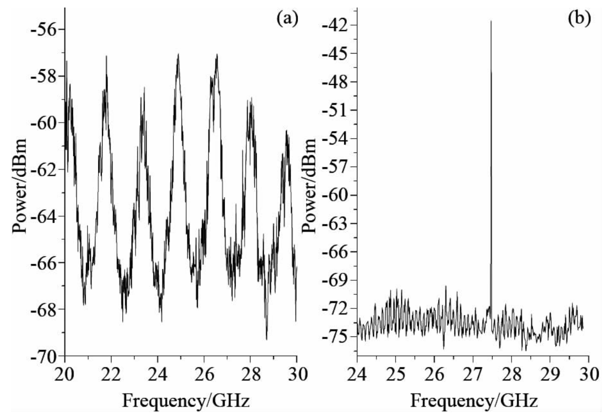

Fig. 3　(a) Output electrical spectrum with only main ring cavity, (b) Output electrical spectrum with main ring and two sub-ring cavities
图 3　(a)在只有主环形腔条件下观察的电频谱图,(b)在复合环形腔条件下观察的电频谱图

The unique feature and innovative point of this technique is reached by using a DMD filter. The DW-SLM lasing can be generated only through producing reconfigurable diffraction gratings to steer lasing wavelengths by utilizing the DMD filter due to the degenerate FWM process of HN-PCF and Vernier Effect of multi-ring cavities. Figures 4 and 5 both show that the wavelength spacing can be smartly adjusted from 3 pixels to 20 pixels with 1 pixel step (i. e., from 0.165 nm to 1.08 nm with a 0.055 nm step). The output spectrum of fiber laser is obtained by an OSA with a resolution of 0.02 nm. When wavelength is 1 pixel or 2 pixels, the mode competition of two SLM wavelengths is too serious to guarantee stable dual-wavelength. The maximum wavelength-spacing tuning range is mainly affected by the PCF type. The nonlinear coefficient and flat dispersion of PCF adopted in the experiment have scope only around 1550 nm. As a homogeneous medium, EDF can produce certain mode competition which is not conductive to generate uniform dual-wavelength. Two degenerate FWM processes caused by the HN-PCF can inhibit the mode competition. The implementation of degenerate FWM process depends on the phase matching conditions, which are heavily dependent on the nonlinear coefficient and flat dispersion. When the wavelength spacing is added to 21 pixels (1.155 nm), the dual-wavelength beyond the scope of HN-PCF, and the dual-wavelength output is non-uniform and unstable. Pump source, optical fiber and diffraction loss of DMD filter have some impact on the wavelength-spacing tuning range. As shown in Figs. 4 and 5, the side mode suppression ratio (SMSR) of the DW-SLM EDFRL keeps above ~40 dB in the tuning range. Combined with Fig. 2 that indicates the theoretical relation (nm and pixel) and Fig. 5 that indicates the experimentally measured relation (nm and pixel), Fig. 6 verifies the compatibility between the wavelength spacing (nm) and wavelength spacing (pixel) by fitting out the relationship between the wavelength spacing and pixel. Figure 6 shows that the measured value basically agrees well with calculated value, which indicates that the DMD filter is well controlled during the experimental process.

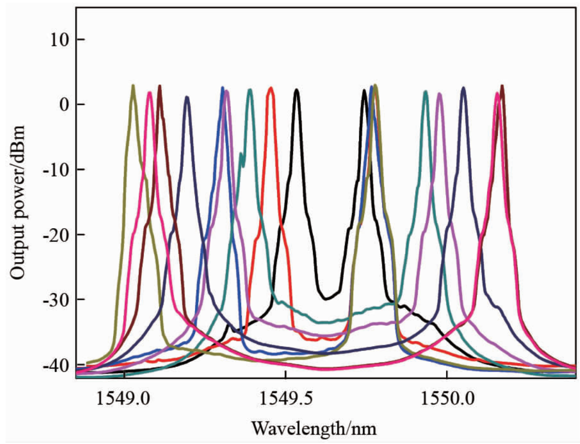

Fig. 4 Integration optical spectra of the EDFRL output with different wavelength spacing

图 4 掺铒光纤环形激光器在不同波长间隔条件下的光谱集成图

In order to investigate the stability of the EDFRL, the dual-wavelength and output power have been measured with 20 times repeated scans at 5 minutes interval in 100 minutes as shown in Fig. 7. In Fig. 7(a), when the wavelength spacing is 3 pixels, the wavelength fluctuations of dual-wavelength at 1549.778 nm and 1 549.916

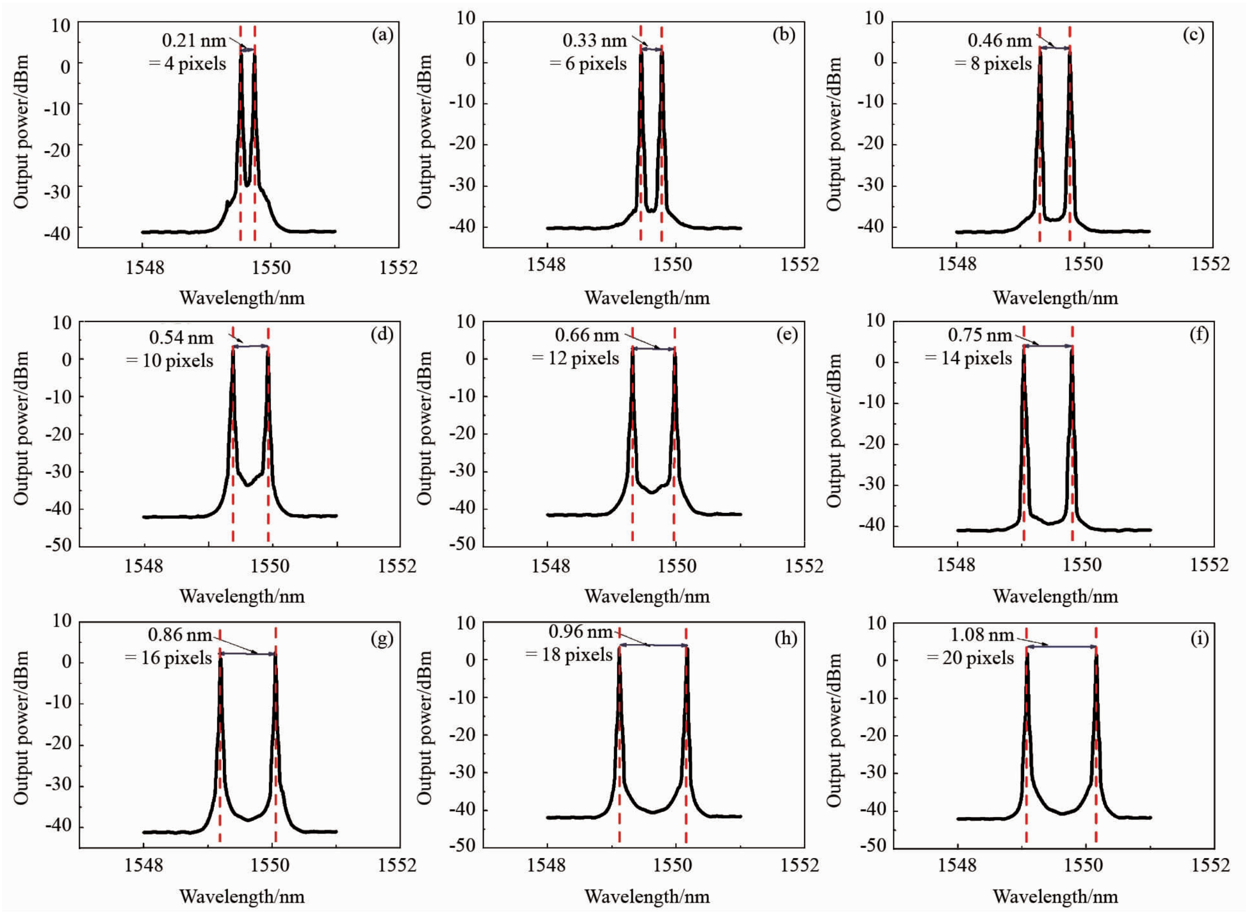

Fig. 5 Specific optical spectrum of the EDFRL output with different wavelength spacing

图 5 掺铒光纤环形激光器在不同波长间隔条件下的光谱图

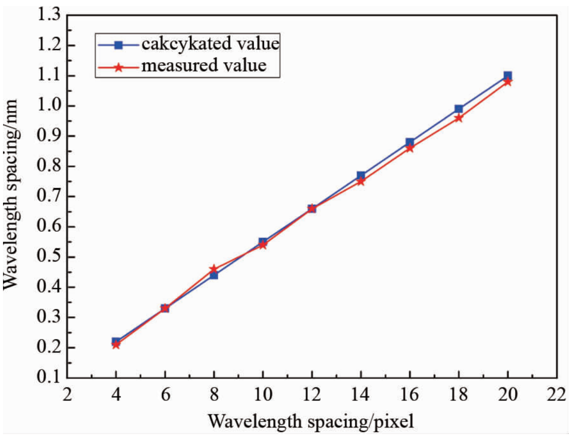

Fig. 6 The fitted curve between wavelength spacing (nm) and wavelength spacing (pixel)
图 6 波长间隔(nm)和波长间隔(像素)的拟合曲线

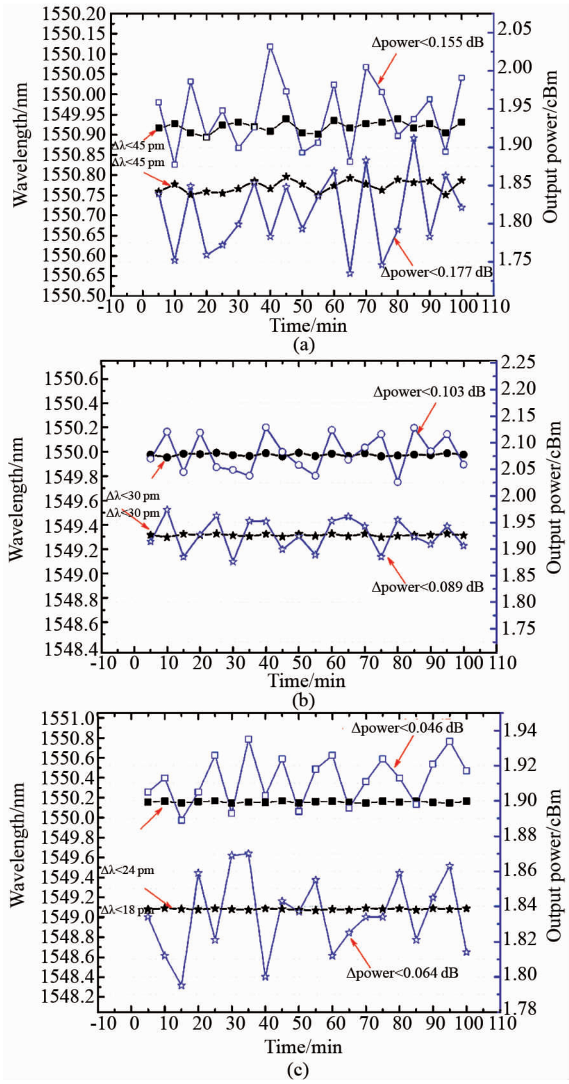

Fig. 7 Measured fluctuations of wavelength lasing and output power (a) wavelength spacing is 3 pixels, (b) wavelength spacing is 12 pixels, (c) wavelength spacing is 20 pixels
图 7 在不同波长间隔条件下,激光器的输出双波长和功率的漂移性 (a)波长间隔是 3 个像素,(b)波长间隔是 12 个像素,(c)波长间隔是 20 个像素

nm are both less than 45 pm, and the output power are less than ~0.177 dB and ~0.155 dB, which means the DW-SLM operation of fiber laser is stable. When we increase the wavelength spacing to 12 pixels, Fig. 7(b) shows that the dual-wavelength variation and output power variation of each wavelength are less than ~30 pm and ~0.103 dB, which means that the DW-SLM EFDRL operation is more stable. In the meanwhile, we also measure the dual-wavelength and output power fluctuation when the wavelength spacing is 20 pixels, as is shown in the Fig. 7(c), we note that the corresponding numerical data are less than ~24 pm and ~0.064 dB, respectively. Therefore, with the increase of wavelength spacing, the fluctuations of output power and dual-wavelength are both decreased, and the EDFRL would tend to a more stable operation with the increase of wavelength spacing.

Finally, in order to further proof the stability of the fiber laser, as shown in Fig. 8, though 15 minutes repeated scanning for 150 minutes, the output power of the dual-wavelength at 1549.08 nm and 1550.156 nm (i.e., the wavelength spacing is 20 pixels) has been also performed. It can be observed that, the DW-SLM EDFRL is very steady and the SMSR can be closed to ~45dB.

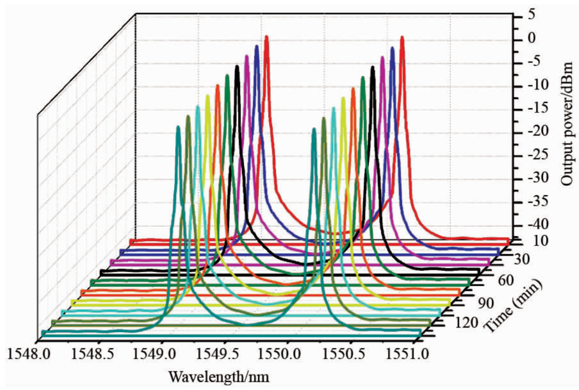

Fig. 8 Measured output spectrum of DW-SLM laser when wavelength spacing is 20 pixels for 150 minutes repeated scanning with a time interval 15 minutes
图 8 当波长间隔为 20 个像素时,双波长单纵模激光器在 150 分钟内的频谱扫描图,扫描间隔为 15 分钟

3 Conclusion

To summarize, we have proposed and experimentally demonstrated a novel configuration for a wavelength-spacing-tunable DW-SLM EDFRL based on a DMD filter, two sub-ring cavities and a section of HN-PCF. The DMD filter can be easily realized tunable dual-wavelength lasing without any mechanically shift. The stability of dual-wavelength can be guaranteed through by using FWM effect of highly nonlinear PCF. The two sub-ring cavities can suppress the mode competition and ensure that the dual-wavelength oscillated in SLM. Because of the flexible adjusting the DMD as a tunable dual-transmission-filter, the interval of dual-wavelength can be transformed from 0.165 nm to 1.08 nm with a tuning accuracy of 0.055 nm. Moreover, the steady of SLM dual-wavelength can get better with the increasing of wavelength spacing.

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