

Three-channel dual-wavelength fiber laser based on a digital micromirror-device processor and photonic crystal fiber

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Received December 14, 2014; accepted January 16, 2015; posted online March 10, 2015

A stable three-channel dual-wavelength fiber ring laser is proposed and experimentally demonstrated. The digital micromirror-device (DMD) processor can select and recirculate any dual waveband from the gain spectrum of the erbium-doped fiber at each channel. The uniform and stable dual-wavelength oscillation is obtained by a highly nonlinear photonic crystal fiber, which causes two degenerate the four-wave-mixing processes. By loading different reproducibility diffraction gratings on the optoelectronic DMD processor, the laser can be operated stably in a three-channel dual-wavelength scheme at room temperature. The power fluctuation of each laser channel is less than ~ 0.02 dB.

OCIS codes: 140.3500, 140.3510, 140.3515.

doi: 10.3788/COL201513.041404.

In recent years, dual-wavelength fiber lasers have been investigated intensively because of their potential applications in optical generation of microwave signals, wavelength division multiplexing, optical fiber sensors, and optical instrument testing^[1,2]. Compared with other lasers, an erbium-doped (ED) fiber ring laser (FRL) has many competitive advantages, such as a flexible experimental structure, low intensity noise, long life pumping, and narrow output line-width. However, the ED fiber is employed as the gain medium in the ED-FRL, and it has a severe homogeneous line broadening effect at room temperature, which leads to the selected dual-wavelength lasing being unstable and nonuniform. To realize a stable and uniform dual-wavelength lasing in ED-FRL, we need to solve this problem.

In this work, we propose and demonstrate a stable three-channel dual-wavelength ED-FRL, which can be utilized as a stable three-channel dual-wavelength lasing generator. The three-channel dual-wavelength lasing is guaranteed by using an optoelectronic (opto)-digital micromirror-device (DMD) processor^[3-5] and three lengths of highly nonlinear (HN) photonic crystal fiber (PCF)^[6-11]. In each channel, the opto-DMD processor can not only select and recirculate two wavelength signals from the amplified spontaneous emission (ASE) spectrum of the ED fiber into its own channel, but also route the laser back into the corresponding fiber ring to generate dual-wavelength signals. The four-wave-mixing (FWM) effect in a HN-PCF can not only alleviate the mode

competition, but also effectively suppress the homogeneous line-broadening effect. In this work, by applying different reproducibility diffraction gratings onto an opto-DMD processor via controlling the software, three-channel stable dual-wavelength lasing can be generated.

The experimental platform for generating three-channel dual-wavelength lasing signals is shown in Fig. 1. It consists of three stable dual-wavelength fiber lasers synchronously controlled by only one opto-DMD processor. The three-channel laser consists of an opto-DMD processor, three 30 m HN-PCFs (a nonlinear coefficient of ~ 11 W⁻¹ km⁻¹ and a flat dispersion of ~ 1 ps/nm/km around 1550 nm), one ED optical fiber amplifier (EDFA), and a 1200 mm⁻¹ blazed grating plate. A microelectromechanical element controls the normal operation of the DMD, which consists of 1024 pixels \times 768 pixels; any waveband of the ASE spectrum can be selected by powering on the operating voltage to the suitable pixel area. Each HN-PCF, which is inserted into the corresponding main ring channel, ensures the stability of the dual-wavelength output. The gain medium of the laser is ED fiber. As a demultiplex filter, the 1200 mm⁻¹ blazed grating plate is used to decompose the ASE spectrum and produce active operation area onto the opto-DMD processor. The output is divided into two parts by a 10:90 1 \times 2 coupler; the 10% part is monitored by an optical spectrum analyzer (OSA), and 90% of output is recirculated into each channel main ring.

The opto-DMD (0.55 in. DMD) processor is the central component of experimental facility and it is a new

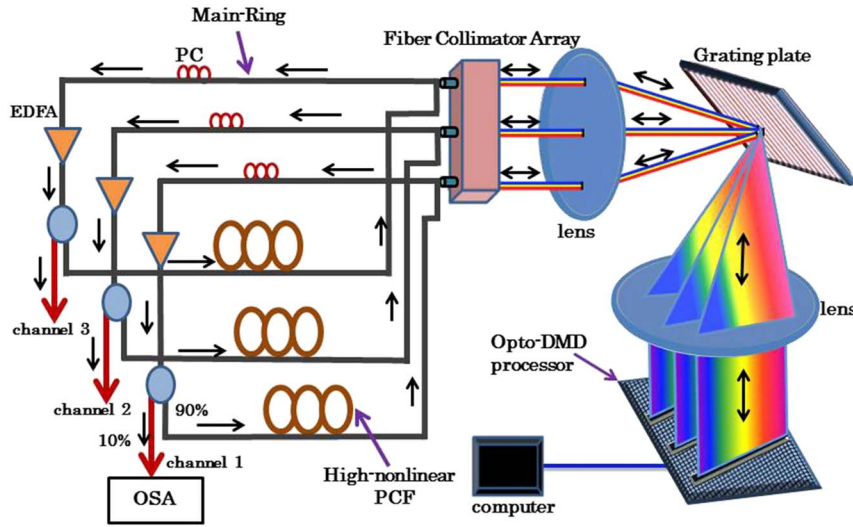


Fig. 1. Experimental setup.

semiconductor optical switch. The opto-DMD processor consists of $1024 \text{ mirror-pixels} \times 768 \text{ mirror-pixels}$, which are integrated in the complementary metal-oxide-semiconductor (CMOS) silicon substrate. Because of the hinge effect of rotating device at the bottom, each independent mirror-pixel can rotate $\pm 12^\circ$ along its diagonal direction. By uploading appropriate voltage on the corresponding mirror-pixel, the unselected part of ASE spectrum of the ED fiber is directly reflecting on the unselected mirror-pixel blocks and will not be coupled into the collimator. Instead, the selected mirror-pixel blocks could be tilted and the target bandwidth can diffract efficiently. Eventually, the opto-DMD processor can realize the purpose of wavelength selection.

The mode competition caused by the ED fiber as a homogeneous medium is detrimental to the output of uniform dual-wavelength. In order to make the two lasing beams stable and uniform, the HN-PCF, which causes two degenerate FWM processes^[6], is inserted into each main cavity. The basic principle of inhibiting mode competition caused by the FWM is to compensate the optical power of different wavelength through the redistribution of beam energies. As the HN-PCF is inserted into the laser cavity, the FWM effect in the HN-PCF, which can restrain the mode competition and the homogeneous gain broadening, is adopted to realize stable dual-wavelength signals. By applying the appropriate different reproducibility diffraction gratings that control three pixel parts of the DMD filter, three separate double-wavelength signals can independently be selected and recirculated in different main fiber ring cavities, thus realizing a three-channel tunable dual-wavelength fiber laser. In order to explain the process of inhibiting mode competition, we take one arbitrary channel as an example in this Letter. Suppose the two wavelengths were selected at λ_1 and λ_2 (corresponding to two frequencies ω_1 and ω_2). The two degenerate FWM processes, namely $\omega_2 + \omega_3 = 2\omega_1$ and $\omega_1 + \omega_4 = 2\omega_2$, can generate another two wavelengths ω_3 and ω_4 . In this Letter, we define P_1 , P_2 , P_3 , and P_4

as the optical powers at the frequencies ω_1 , ω_2 , ω_3 , and ω_4 , and they can be obtained as

$$P_3 = \gamma^2 L^2 P_1^2 P_2, \quad (1)$$

$$P_4 = \gamma^2 L^2 P_2^2 P_1, \quad (2)$$

where the parameter γ represents the nonlinear coefficient of the fiber, and L is the interaction length of the FWM. The corresponding augment of powers at ω_1 and ω_2 , namely ΔP_1 and ΔP_2 , originated from ω_2 and ω_1 , respectively. In our work, two photons of frequency ω_1 are annihilated to produce one photon of frequency ω_3 , another photon of frequency ω_2 , and $\omega_3 \approx \omega_2$, so ΔP_2 can be determined as

$$\Delta P_2 \approx P_3 = \gamma^2 L^2 P_1^2 P_2. \quad (3)$$

A similar procedure plays the same role in the value of ΔP_1

$$\Delta P_1 \approx P_4 = \gamma^2 L^2 P_2^2 P_1. \quad (4)$$

As a conclusion, the difference ΔP between ΔP_1 and ΔP_2 can be determined as

$$\Delta P = \Delta P_1 - \Delta P_2 = \gamma^2 L^2 P_1 P_2 (P_2 - P_1). \quad (5)$$

Therefore, when $P_2 > P_1$, then $\Delta P > 0$, and the energy are transferred from ω_2 to ω_1 ; whereas when $P_2 < P_1$, then $\Delta P < 0$, and the energy are transferred from ω_1 to ω_2 . Under the action of two degenerate FWM, the two beams lasing become stable and uniform at the room temperature.

The dual-wavelength emitting spectra of the proposed three-channel ED-FRL are shown in Fig. 2. In order to make the three laser channels for lasing output at the same time, the pixel region of the DMD filter was partitioned into three independent parts; each part corresponds to

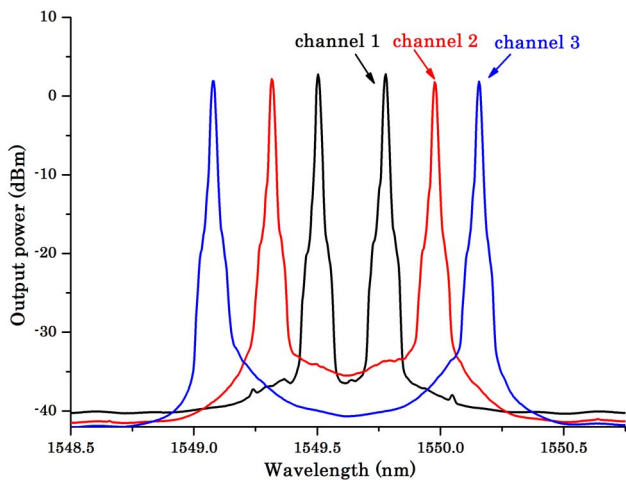


Fig. 2. Observed output spectrum of the three-channel dual-wavelength signals at the same time. Corresponding wavelength interval for Channels 1–3 are 4 pixels (0.21 nm), 12 pixels (0.65 nm), and 18 pixels (0.98 nm), respectively.

the ASE spectrum of the ED fiber and specializes in generating double-wavelength signals at the corresponding channel. In the process of lasing generation, three different reproducibility diffraction gratings were applied to the three pixel parts, such that the corresponding three ASE dual-wavebands could be filtrated and recirculated into their own fiber ring channel. In our work, the function of the opto-DMD processor is similar to a wavelength selector. The wavelength changed 0.055 nm per pixel shift (i.e., 0.055 nm/pixel) via operating computer software. Figure 2 shows the wavelength interval of the double wavelengths from Channels 1–3 are 4, 12, and 18 pixels, respectively (i.e., 0.21, 0.65, and 0.98 nm, respectively). The output of dual-wavelength signals can be realized only through producing reproducibility diffraction gratings to control wavelengths lasing by utilizing an opto-DMD processor due to the degenerate FWM process of HN-PCF.

In order to prove that the each laser channel has the ability to complete the independent dual-wavelength lasing, the output spectra of Channels 1–3 were measured. Figure 3 demonstrates the dual-wavelength lasing and coarse wavelength spacing tuning capabilities of the three-channel fiber laser. The three-channel dual-wavelength lasers could realize the independent control of an individual channel, and can achieve good stability at room temperature conditions under the different wavelength intervals. When the wavelength interval is 0.21, 0.65, and 0.98 nm, each channel has an output power level of ~ 2.14 dBm, and the side mode suppression ratio (SMSR) is about ~ 40 dB. Figure 3 also roughly illustrates that the output power shift at each channel is very small during the observation period of different wavelength spacings. Due to the generation of stable three-channel dual-wavelength signals that can be guaranteed by means of a DMD filter without any mechanical movement, the output signals are insensitive to the environment vibration. In particular, the diffraction loss of opto-DMD is the most important factor

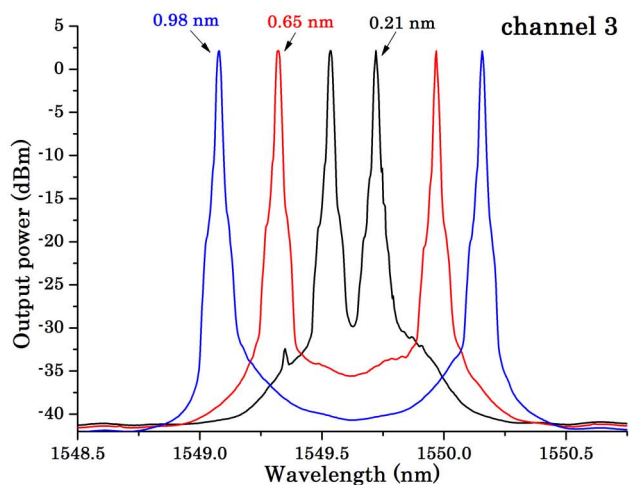
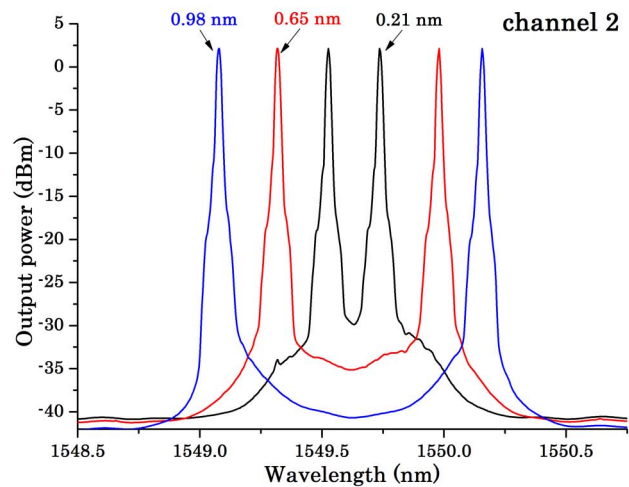
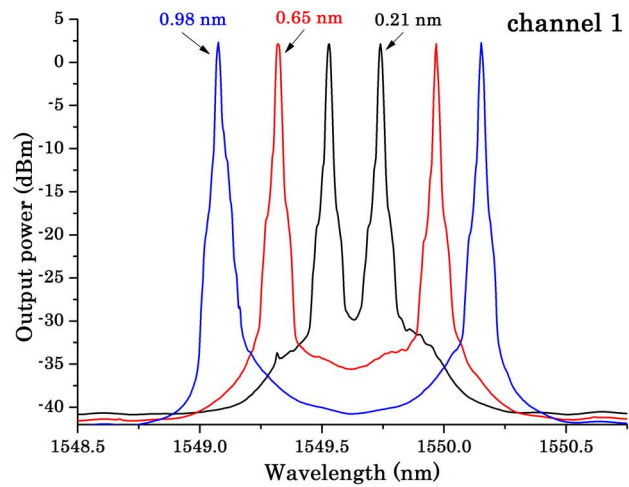


Fig. 3. Observed output spectrum of the three-channel dual-wavelength signals at different times. Three channels can independently and simultaneously realized dual-wavelength lasing.

which affects the stability of three-channel fiber ring laser lighting and output quality.

In order to investigate the stability of the three-channel ED-FRL, the output power of each channel has been measured with 15 repeated scans at 10 min intervals in 150 min as shown in Fig. 4. At Channel 1, when the

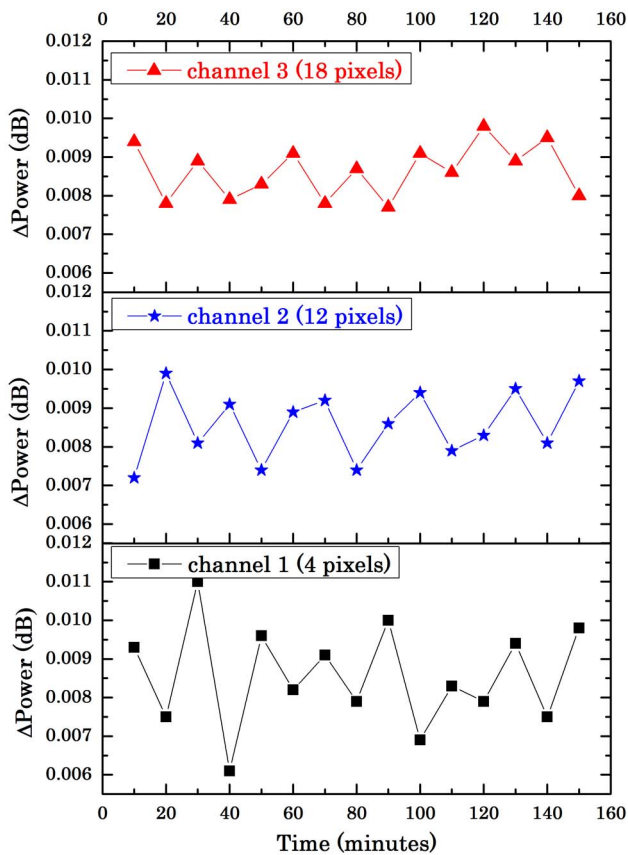


Fig. 4. Measured fluctuation of laser output power. Channel 1, wavelength interval 4 pixels (0.21 nm); Channel 2, wavelength interval 12 pixels (0.65 nm); Channel 3, wavelength interval 18 pixels (0.98 nm).

wavelength interval is 4 pixels, the fluctuation of the output power difference of dual-wavelength is less than ~ 0.05 dB, which means the dual-wavelength operation of the fiber laser is stable. At Channel 2, we increase the wavelength interval to 12 pixels; the output power difference of dual-wavelength is less than ~ 0.03 dB, which represents that the laser operation is more stable. We also measured the output power fluctuation when the wavelength interval is 18 pixels at Channel 3; note that the corresponding numerical data is less than ~ 0.02 dB. Therefore, with the increase of the wavelength interval, the fluctuation of the output power difference is decreased, and the three-channel dual-wavelength ED-FRL would tend to a more stable operation in accordance with the increase of the wavelength spacing.

Finally, in order to further analysis the stability of the three-channel dual-wavelength fiber laser, as shown in Fig. 5, the dual-wavelength lasing at Channel 1 has been measured though 15 min repeated scanning for 150 min, and the wavelength interval is about ~ 0.21 nm. It is clearly visible that the dual-wavelength ED-FRL is very steady and the SMSR remains at ~ 40 dB in the tuning range. With the increase of sweeping time, the fluctuation of the dual-wavelength is decreased, and a more-stable three-channel dual-wavelength lasing can be achieved.

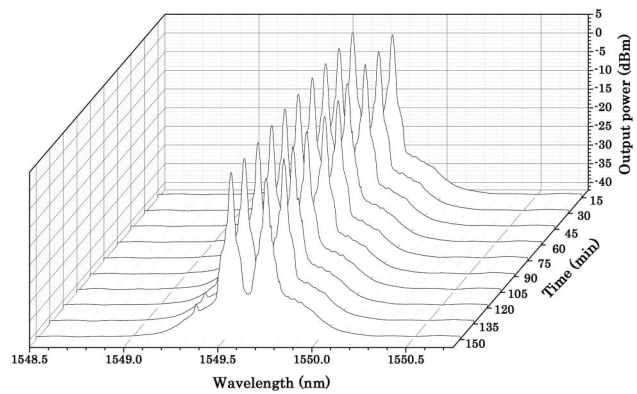


Fig. 5. Measured output spectrum at fixed wavelength spacing of 4 pixels for Channel 1 and at $10\times$ repeated scanning spectra with a time interval of 15 min.

In conclusion, a novel configuration for a three-channel dual-wavelength ED-FRL by incorporating a single DMD processor and three sections of HN-PCF is proposed and experimentally demonstrated. The uniform stability of double wavelength can be guaranteed through by using FWM effect of the HN-PCF. By regulating the DMD as a three-channel dual-transmission filter, our work shows that the three-channel laser has the capacity of independently and simultaneously oscillating three dual-wavelength lasing, can achieve a higher SMSR of about ~ 40 dB, and a good power difference less than ~ 0.02 dB. Moreover, the steady of three-channel dual-wavelength lasing can become more smooth in accordance with an increasing wavelength interval.

This work was supported by the National Basic Research Program of China (2010CB327600), the Fundamental Research Funds for the Central Universities (2013RC1202), the Specialized Research Fund for the Doctoral Program of Higher Education (20120005120021), the Program for New Century Excellent Talents in University (NECT-11-0596), and the Beijing Nova program (2011066).

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