Demonstration of multi-wavelength tunable fiber lasers based on a digital micromirror device processor

Qi Ai, Xiao Chen, Miao Tian, Bin-bin Yan, Ying Zhang, Fei-jun Song, Gen-xiang Chen, Xin-zhu Sang, Yi-quan Wang, Feng Xiao, and Kamal Alameh

1College of Science, Minzu University of China, Beijing 100081, China
2State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing 100876, China
3Electron Science Research Institute, Edith Cowan University, Joondalup WA 6027, Australia
*Corresponding author: xchen@pku.edu.cn

Received 9 October 2014; revised 10 December 2014; accepted 10 December 2014; posted 12 December 2014 (Doc. ID 224159); published 22 January 2015

Based on a digital micromirror device (DMD) processor as the multi-wavelength narrow-band tunable filter, we demonstrate a multi-port tunable fiber laser through experiments. The key property of this laser is that any lasing wavelength channel from any arbitrary output port can be switched independently over the whole C-band, which is only driven by single DMD chip flexibly. All outputs display an excellent tuning capacity and high consistency in the whole C-band with a 0.02 nm linewidth, 0.055 nm wavelength tuning step, and side-mode suppression ratio greater than 60 dB. Due to the automatic power control and polarization design, the power uniformity of output lasers is less than 0.008 dB and the wavelength fluctuation is below 0.02 nm within 2 h at room temperature. © 2015 Optical Society of America

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (140.3600) Lasers, tunable.

http://dx.doi.org/10.1364/AO.54.000603

1. Introduction

Wavelength-tunable filters, which are among the key devices, have been widely applied in wavelength division multiplexing and all optical switching systems. Multi-wavelength tunable filters, compared with commercialized single-wavelength filters, involve much more complex technical problems. Recently, several versatile techniques have been proposed including a spatial mode beating filter [1], fiber Bragg gratings [2], a Fabry–Perot fiber cavity [3], fiber-loop mirror filters based on polarization-maintaining (PM) fiber [4], Mach–Zehnder interferometers [5], and liquid crystal on silicon [6]. However, the current approaches mostly suffer from limited tunability and flexibility, poor stability, polarization dependence, and narrow operation ranges.

In this paper we propose a digital micromirror device (DMD) as a narrow-band tunable filter and first apply it to tune multi-wavelengths in the fiber laser. The key property of this DMD-based fiber laser is that any lasing wavelength from any output port can be switched independently only by one software-driven DMD chip. All wavelengths can be tuned flexibly from 1530 to 1560 nm with the step 0.055 nm. The side-mode suppression ratio (SMSR) of signals is greater than 60 dB, which is higher than most of the reported tunable fiber lasers [7–10]. The maximum output power is about 10 mW. Due to the automatic power control and polarization design, the power uniformity of an output laser is less than 0.008 dB and the wavelength fluctuation is below 0.02 nm within 2 h at room temperature, respectively.

2. Laser Structure and Operation Principle

Figure 1 is the schematic diagram of an M-port tunable fiber laser. It consists of the PM fiber module
and the bulk optics module. The fiber module contains $M$ fiber loops with $M$ output ports. For each loop it includes PM erbium-doped fiber amplifiers (EDFA) operating in the C-band, a $1 \times 2$ PM fiber coupler with 10/90 power splitting ratio, and a dual PM fiber collimator. The bulk optics module includes two lenses, a blazed grating and a 0.55° DMD processor. The design of whole-bulk optics is a typical 4-f imaging system. The operation principle of one fiber laser loop can be referred to [11]. In the experiment a blazed grating with 1200 lines/mm is used to demultiplex the amplified spontaneous emission (ASE) spectrum from an EDFA, and then ASE as collimated light linearly maps onto the active window of a DMD processor by lens 2. The DMD is a semiconductor-based 1024 × 768 array of addressable mirror-pixels with the pitch 10.8 μm. All micro-mirrors can be individually rotated ±12° along each diagonal line. By uploading the appropriate hologram onto the DMD, the corresponding mirrors are driven to tilt so that a part of diffraction light from ASE is coupled back nearly along the incident path into the collimator while the others are dropped out. After several recirculations the high-quality single-mode laser is achieved. It is important to note that in order to increase the SMSR of signals, the approximate blazed condition of the DMD over the whole C-band should be satisfied, which we have discussed in [12].

For the multi-wavelength tunable fiber laser with multiple output ports, the attractive architecture is that multiple fiber loops share one set of bulk optical components. It makes the whole system very compact. Besides, only driven by one DMD chip, multi-wavelengths can be tuned independently and flexibly. Figure 2 displays a DMD partitioned into $M$ rectangular pixel-blocks, and each pixel block is assigned to one laser ring. By uploading the optimized phase holograms onto a DMD, $M$ independent wavelengths can be selected for lasing within the different fiber loops. It thus realizes an $M$-port tunable fiber-laser source that simultaneously generates arbitrary lasing wavelengths at its ports. Considering the active window of a 0.55° DMD used in experiment and avoiding the crosstalk between ports/ channels, we choose three output ports to proof the principle.

### 3. Experimental Results

The ASE noise from an EDFA is shown in Fig. 3 and the inset is the arbitrary wavelength selected by the DMD processor when the optical loop is open. The measured total loss of bulk optics from input and output collimators is around 11.6 dB, which is mainly due to the lens reflection loss, the diffraction loss, and the insertion loss from the blazed grating and DMD processor. The largest loss among them is caused by the DMD [12,13]. The total cavity loss, as one of the key parameters, not only influences the output power and SMSR, but also the EDFA pump current thresholds needed for lasing [14].

After the laser loop was closed, the DMD was driven by different phase holograms and each corresponds to single-mode lasing at a specific wavelength. Figure 4 illustrates the typical signal with the center wavelength 1549.7 nm. The SMSR is over 60 dB, which is higher than that of most of the commercialized tunable lasers. Compared with the linewidth when the loop is open, the spectral linewidth of lasing signals becomes narrower, to 0.02 nm, and is limited by the spectrometer. The maximum output power is about 10 mW and the adjusting step can be set at 0.01 mW depending on the pumping current of an EDFA.

During the multi-wavelength tuning process, multiple phase holograms are mapped on to the different areas along dispersion bars on the DMD.

![Fig. 1. Schematic diagram of experimental setup.](image1)

![Fig. 2. Distribution of light dispersion bars on a DMD processor.](image2)

![Fig. 3. ASE noise from an EDFA and the inset is the arbitrary wavelength selected by the DMD processor when the optical loop is open.](image3)
processor in order to steer different wavelengths. For three-wavelength tuning in our experiment we first balance the diffraction efficiency, the number of channels, and the crosstalk between ports/channels so as to determine the appropriate size of a hologram. The larger a hologram is the more pixels are involved to diffraction, which helps to increase the efficiency. However, it will decrease the channels number and worsen the crosstalk. It is proved an $8 \times 180$ phase hologram is optimized. Figures 5(a)–5(c) are the output signals by coarse-tuning from 1530 to 1560 nm at three ports, respectively. They demonstrate an excellent tuning capacity and high consistency in the whole C-band. The fine-tuning around 1550 nm is also displayed in Fig. 5(d) with the tuning step 0.055 nm. This tuning step is realized by translating an $8 \times 180$ hologram one pixel forward (backward) along the dispersion bar. This tuning step can be further optimized via selecting a lens 2 with longer focal length or a DMD processor with smaller pixel pitch.

In Figs. 6 and 7 the fluctuations of measured laser wavelengths and output powers near 1550 nm within 2 h are less than 0.02 nm and 0.008 dB, respectively. Due to the whole PM fiber component used in the module and the automatic power control system, the laser output retains higher stability and larger output power than those in the nonpolarization-maintaining system [11]. Besides, the tunable fiber laser can be configured flexibly in the sweeping mode. That is, the output wavelength can scan automatically in a certain waveband by software-uploading a series of holograms continuously on the DMD. The sweeping speed is limited by the loading time of holograms onto a DMD. The sweeping step can be adjusted easily by changing the moving pixels of holograms. Figure 8 shows that ports 1 and 2 work at fixed wavelengths of 1544.486 and 1550.502 nm, respectively, while port 3 sweeps from 1545 to 1550 nm.

![Fig. 4. Typical signals from the tunable fiber laser at an arbitrary port.](image)

![Fig. 5. Laser signals covering the whole C-band by coarse-tuning from three ports, respectively, (a)–(c) and by fine-tuning around 1550 nm from (d) an arbitrary port.](image)
4. Conclusions

We experimentally demonstrate a multi-port tunable fiber laser based on erbium-doped fibers as the laser gain medium and a DMD processor as a narrow-band multi-wavelength filter. The attractive structure of this tunable fiber laser is that multi-wavelengths can be tuned flexibly and independently only by one DMD chip. The experimental results show that the output-lasing wavelength from all ports can be shifted easily over the C-band with the tuning step 0.055 nm, which is more practical than the traditional tunable fiber lasers. The side-mode suppression ratio of signals is above 60 dB, which is higher than most of commercialized fiber lasers. The maximum output power is 10 mW with the step 0.01 mW. The fluctuations of center wavelengths from all output ports are all below 0.02 nm within 2 h. All wavelengths can work flexibly in the fix mode and sweeping mode.

We acknowledge the financial support from the National Science Foundation of China (11204387), the Key Project of Science and Technology from Ministry of Education of China (212205), the 985 Project (Grant No. 98507-010009, 98504-012004), and the 211 Project of Ministry of Education of China.
References