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Employment of silicon-micro-ring resonator and compound-ring architecture for stable and tunable single-longitudinal-mode fiber laser

Yung Hsu [a], Chien-Hung Yeh [b,*], Hao-Yun Cheng [b], Yuan-Chia Chang [a], Chi-Wai Chow [a]

[a] Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan
[b] Department of Photonics, Feng Chia University, Taichung 40724, Taiwan

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ABSTRACT

In this work, a wavelength-switchable erbium-doped fiber (EDF) glasses-type compound-ring (GTCR) laser with stable single-longitudinal-mode (SLM) oscillation is proposed and presented. In the experiment, to accomplish wavelength-tunable operation, a silicon-micro-ring-resonator (SiMRR) is utilized inside the ring cavity, when the birefringent loss of EDF laser is adjusted properly. Moreover, the GTCR configuration is proposed to as the mode-filter for suppressing the multi-longitudinal-mode (MLM) to achieve the SLM oscillation. Here, the measured linewidth of output wavelength is ~61 kHz. The output stabilities of the proposed SiMRR EDF compound-ring laser are also discussed experimentally.

1. Introduction

Single-longitudinal-mode (SLM) erbium-doped fiber (EDF) lasers with stable output and broadband tuning range are attractive light sources for the beneficial applications, such as in the optical communications, optical sensing, material processing, optical spectroscopy and instrument, medical diagnostics, and optical imaging [1–7]. Furthermore, the EDF-based lasers are promising and interesting because they can provide stable and tunable single-frequency output. Therefore, to achieve the SLM EDF laser, there are several crucial techniques have been proposed to suppress the densely multi-longitudinal-mode (MLM) oscillation, such as using the Fabry-Pérot laser diode (FP-LD) [8], the saturable absorber (SA)-based filter [9,10], the multi-fiber-ring (MFR) scheme [11,12], and birefringent fiber filters [13] in the ring cavity of fiber lasers. Moreover, to accomplish the wavelength-tuning operation, the fiber Bragg grating (FBG), tunable bandpass filter (TBF), highly nonlinear photonic crystal fiber, and silicon-micro-ring resonator (SiMRR) have been utilized inside the fiber cavity [14–17].

Recently, the use of silicon-on-insulator (SOI) based integrated photonic optical components [17] for EDF lasers are attractive because they are compact in size and potentially low cost. The silicon photonics are compatible with the large volume manufacturing at silicon fabrication foundries. According to the recent development of SOI, it will be very interesting to utilize a silicon-micro-ring resonator (SiMRR) to build a distinctive fiber laser [18,19].

In this demonstration, we propose and illustrate a stable and wavelength-switchable EDF glasses-type compound-ring (GTCR) laser scheme with SLM output by using the SiMRR for tunability. To achieve the SLM lasing, a GTCR cavity structure is illustrated in the EDF laser for compressing MLM. Here, the lasing wavelength can be tuned in the wavelength range of 1529.29 nm to 1560.24 nm with ~2 nm tuning step. The measured output powers and optical signal to noise ratios (OSNRs) are between 3.6 and 5.2 dBm and 24.7 and 38.7 dB, respectively. The obtained 3 dB linewidth of output wavelength is ~61 kHz. Moreover, during 30 min stability evaluation, the maximum output wavelength and power fluctuations are small than 0 nm and 0.9 dB, respectively.

2. Experiment and results

The proposed SiMRR-based EDF compound-ring laser architecture is illustrated in Fig. 1(a). The experimental setup is constructed by a SiMRR device, a commercial C-band erbium-doped fiber amplifier (EDFA) having the saturated output power of 13 dBm, two polarization controllers (PCs), an in-line polarizer (POL), a 2 × 2 50:50 optical coupler (OCP_1), and three 1 × 2 50:50 OCPs (OCP_2, OCP_3 and OCP_4), respectively. Four OCPs are used to produce a glasses-type compound-ring (GTCR) configuration for acting as the mode-filter, as also exhibited in Fig. 1(a). Besides, the available gain of C-band EDFA is 25 dB in the effective range of 1528.0–1564.0 nm. Here, the two PCs and POL are utilized to maintain the polarization status and retrieve maximum output

* Corresponding author.
E-mail address: yehch@fcu.edu.tw (C.-H. Yeh).

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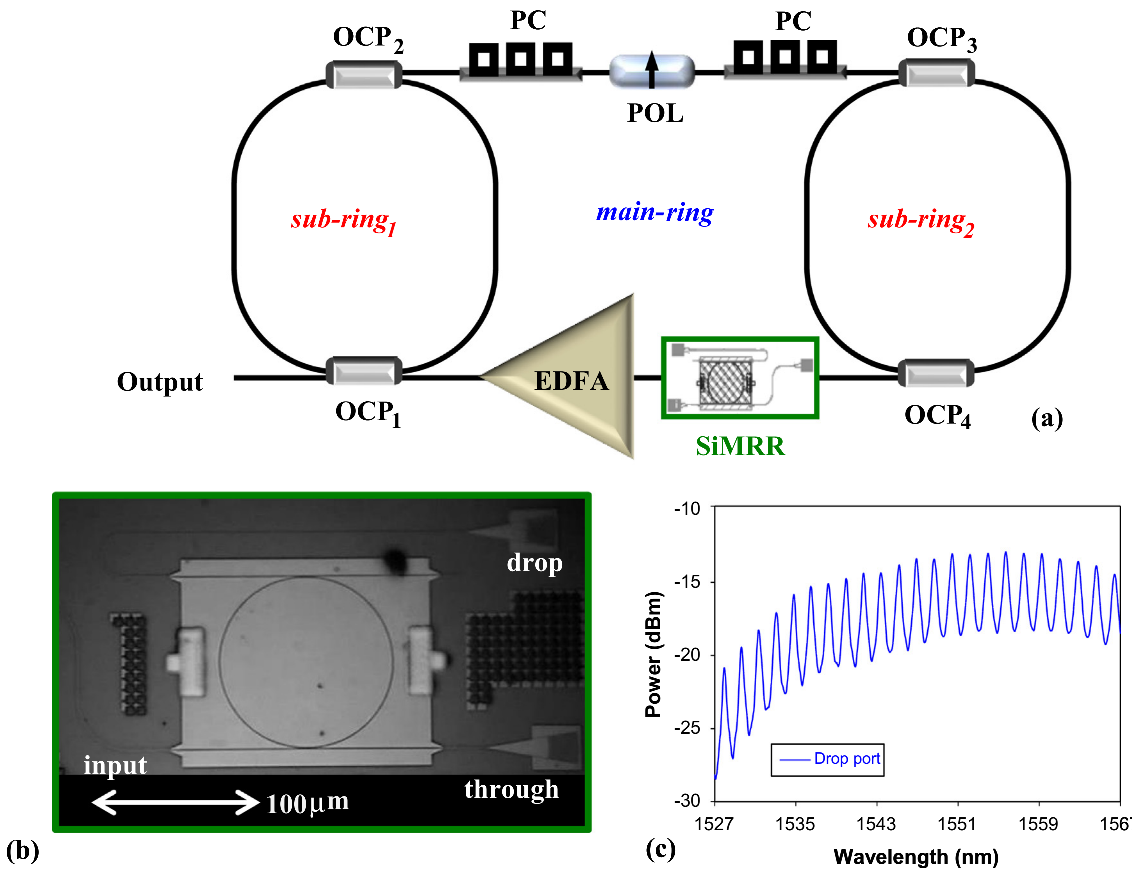

Fig. 1. (a) Experimental setup of proposed wavelength-switchable SLM fiber laser using SiMRR. (b) The microscope image of SiMRR with three ports. (c) Measured SiMRR filtered output spectrum of drop port.

power in the proposed EDF laser. The SiMRR is used for tuning different output wavelengths, while the birefringence loss of proposed EDF laser is attuned properly by controlling two PCs.

Fig. 1(b) presents the scanning electron microscope (SEM) graph of the SiMRR. In the experiment, the 193 nm deep-ultra-violet (DUV) lithography and reactive-ion etching (RIE) methods are applied to manufacture the SiMRR on a silicon-on-insulator (SOI) wafer. Here, the top silicon layer is 0.22 μm and the burial oxide (BOX) layer of SOI is 2 μm, respectively. Moreover, the length and width of the input and output waveguide grating couplers are 14 and 9 μm, respectively. And the etch depth and period of waveguide grating coupler are 70 and 580 nm, respectively. The designed diameter of SiMRR is ~100 μm, as indicated in Fig. 1(b).

Here, the amplified spontaneous emission (ASE) of C-band EDFA would pass through the OCP_1, OCP_2, two PCs, POL, OCP_3 and OCP_4, respectively. Then, the ASE source is launched into the input port of SiMRR by utilizing the silicon waveguide grating coupler (SiWGC), as seen in Fig. 1(a). Moreover, to connect to the single-mode fiber (SMF) and the SiWGC, around vertical coupling with a vertical offset angle of 10° is employed [20]. Next, the ASE source would leave from the drop port of SiMRR and then into EDFA for amplification. Finally, the generated output wavelength of proposed EDF laser can be observed at the output port of OCP_1 and measured by an optical spectrum analyzer (OSA) with a 0.06 nm resolution. Besides, Fig. 1(c) show the measured spectrum of SiMRR at the drop port when the output ASE spectrum is used to launched into the SiMRR. As seen in Fig. 1(c), the free spectrum range (FSR) of 2.0 nm can be observed according to its original design.

As seen Fig. 1(a), to complete the SLM oscillation, a GTCR is proposed to produce the mode-filter effect for suppressing the densely MLM. Here, the length of triple-fiber-ring, which represents the main-ring (R_{main}), $sub\text{-}ring_1$ (R_{sub1}) and $sub\text{-}ring_2$ (R_{sub2}) are 30, 3, and 1.5 m, respectively. Moreover, each fiber ring has its corresponding free spectrum range (FSR), which means the FSR_{main}, FSR_{sub1} and FSR_{sub2} respectively, based on its corresponding fiber length [12]. Hence, the obtained FSR_{main}, FSR_{sub1} and FSR_{sub2} are 6.8, 68.1 and 136.2 MHz respectively. Thus, based on Vernier effect, the least common multiple of the three FSRs would result in an effective FSR (FSR_{EFF}) for filtering the MLM. The schematic diagram of each FSR for mode selection is shown in Fig. 2. Moreover, comparing with the previous single-ring case [20], the proposed EDF triple-ring laser has fewer selected mode and less mode competition effect. As a result, the SLM oscillation and mode stability can be guaranteed.

To tune the different wavelengths of proposed SiMRR-based EDF GTCR laser, we can control the two PCs for producing the different birefringence losses and keeping the optimal output power. Fig. 3 indicates measured output wavelengths of proposed EDF triple-ring laser in the operation range of 1529.29–1560.24 nm. Here, thirteen output wavelengths can be observed with a tuning interval of ~2 nm. Fig. 4 presents the observed output power and optical signal to noise ratio (OSNR) in the wavelengths of 1529.29–1564.24 nm. However, there are several lasing modes cannot be obtained in the range of 1535–1543 nm, as exhibited in Fig. 4, due to the losses of SiWGC and SiMRR in these modes possibly. The measured losses of SiWGC and SiMRR are around 8–10 dB. The obtained output powers and OSNRs of the proposed EDF laser are in the ranges from 3.6 to 5.2 dBm and 24.7 to 38.7 dB respectively. In the measurement, the highest power of EDFL is 5.2 dBm in the proposed SiMRR-based EDF ring laser