Beam Combining of SOA-based Bidirectional Tunable Fiber Compound-ring Lasers with External Reflectors

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Abstract: A simple, stable and inexpensive dual- output port widely tunable semiconductor optical amplifier-based fiber compound-ring laser structure is demonstrated. This unique nested ring cavity enables high optical power to split into different branches where amplification and wavelength selection are achieved by using low-power SOAs and a tunable filter. Furthermore, two Sagnac loop mirrors which are spliced at the two ends of the ring cavity not only serve as variable reflectors but also channel the optical energy back to the same port without using any high power combiner. More than 98% coherent beam combining efficiency of two parallel nested fiber ring resonators is achieved over the C-band tuning range of 30 nm. Optical signal to noise ratio (OSNR) of + 45 dB, and optical power fluctuation of less than ± 0.02 dB are measured over three hours at room temperature.

1 INTRODUCTION

All-single-mode fiber resonators of different types, such as linear (He et al., 2009), Fox-Smith (Barnsley et all., 1988), ring, and compound fiber ring (Zhang and Lit, 1994;) cavities have been theoretically and experimentally explored in designing various kinds of fiber laser sources with single-longitudinal mode operation for low and high optical power applications for optical communication systems, scientific, medical, material processing and military purposes (Shi et al., 2014). Adjustable, scalable output optical power and wavelength tunability properties of a fiber laser source are of a great interest in the aforementioned applications that require high optical power. Complex and expensive in-line variable optical attenuators (VOA) with adjustable insertion losses are usually used to control the output power level of laser sources. Mechanical, micro-electromechanical (Syms et al., 2004;), acousto-optic (Li et al., 2002) methods as well as optical fiber tapers (Benner et al., 1990) and hybrid microstructure fiber-based techniques (Kerbage et al., 2001) are widely used to adjust the insertion losses of the in-line fiber-based VOA. However, all-fiber based low power variable reflectors, such as Sagnac loop mirrors (SLMs) can also be used to control the amount of optical power from low and high power fiber laser sources. All-single-mode fiber-based SLMs have been widely used in high sensitivity sensors, such as temperature (Lim et al., 2010), and strain (Sun et al., 2007) sensors. Moreover, the SLMs with adjustable reflectivity have been used to form Fabry-Perot linear resonators (Ummy et al., 2011) where the amount of the output optical power from the resonators depends on the reflectivity of the SLMs (Mortimore, 1988). In this work, two SLMs were used to control the amount of optical power delivered from two output ports of the proposed fiber compound-ring laser. In addition, inexpensive two low power semiconductor optical amplifiers (SOAs) were placed in two parallel nested ring cavities to demonstrate the possibility of achieving a highly power scalable, adjustable and switchable fiber laser structure based on multiple nested compound-ring cavities formed by NxN fiber couplers with two SLM output couplers.

Different methods have been utilized to scale up optical power of laser sources where beam combining has shown to be a promising alternative technique of achieving high power by scaling up multiple combined laser elements. High power laser

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sources with high beam quality have been demonstrated by using complex coherent and spectral beam combining techniques in external cavities (Klingebiel et al., 2007; Augst et al., 2009). In addition, incoherent beam combining method (Sprangle et al., 2009) has been used to scale up the optical power by combining individual laser elements as well. Michelson, Mach-Zehnder resonators were mostly used in coherent beam combining in order to achieve high combining efficiency and nearly diffraction-limited beam quality (Sabourdy et al., 2003). Moreover, ring resonators have proven to be efficient and stable (Jeux et al., 2012) for passive coherent beam combining method.

In order to achieve high power laser sources with high beam combining efficiency, all the aforementioned methods require sophisticated high power external optical components such as micro-lenses, isolators, circulators, photonic crystal fibers and master oscillator pre-amplifiers that are usually complex and very expensive. In addition, rare-earth, ytterbium doped fiber amplifiers (Jeux et al., 2012) or erbium doped fiber amplifiers (EDFAs) (Kozlov et al., 1999) that are usually used as gain media for beam combining to achieve high power laser systems also need to be pumped with other types of laser sources, which makes them very inefficient. However, by using nested compound-ring cavities where circulating beams are equally split in N-number of low power beams that can be amplified by N-number of low power SOAs, one can achieve high efficient and high power laser system that does not require the extra pump lasers or master oscillator pre-amplifiers or other expensive external high power optical components.

Semiconductor optical amplifier (Moon et al., 2007), stimulated Raman scattering (SRS) amplifier (Kim et al., 2003) and stimulated Brillouin scattering (SBS) amplifier (Smith et al., 1991) have also been used as gain media in different fiber laser systems. However, the SOAs are more advantageous than their above-mentioned counterparts, because they are compact, light, less expensive, efficient, and available for different operational regions from a wide range of wavelength spectrum. Moreover, when the SOAs are used in bidirectional fiber ring resonators, they do not require the extra optical components such as optical isolators and optical circulators; as a result, they are easy to integrate with other optical components for compact fiber laser systems.

In this work, we demonstrate a novel technique for coherent beam combining method based on passive phase-locking mechanism (Bruesselbach et al., 2005) of two C-band low power SOAs-based all-single-mode fiber compound-ring resonators by exploiting beam combining (i.e. interference) at 3dB fiber couplers that connect two parallel merged ring cavities. Unlike previous work (Ummy et al., 2016) where non-adjustable multimode fiber laser output formed by a high power and expensive power combiner with a multimode output fiber (i.e. , low brightness) has been replaced by two low power Sagnac loop mirrors to create all-single-mode fiber-based dual-output port laser structure with switchable and adjustable output power. In addition, the single-mode performance is maintained in order to improve the brightness at the proposed fiber compound-ring laser output port. The output power of the proposed combined fiber compound-ring resonators with two low power SOAs was almost twice as large as the output power obtained from a single SOA based- fiber ring or Fabry-Perot linear resonator (Ummy et al., 2011). More than 98% beam combining efficiency of two parallel nested fiber ring resonators is demonstrated over the C-band tuning range of 30 nm. Optical signal to noise ratio (OSNR) + 45 dB, and optical power fluctuation of less than ± 0.02 dB are measured over three hours at room temperature.

2 EXPERIMENATL SETUP

Fig.1 illustrates the experimental diagram of the C-band SOA-based tunable fiber laser with two nested ring cavities (i.e., compound-ring cavity) and two broadband SLMs that serve as either dual output ports or a single output port according to the reflectivity settings of each of the SLMs. Each ring cavity consists of two branches I-II, I-III, for the inner and outer ring cavity, respectively. Both ring cavities share a common branch, I, which contains an SOA_1, (Kamelian, OPA-20-N-C-SU), a tunable optical filter (TF-11-11-1520/1570), and a polarization controller, PC_1. Branch II contains an SOA_2 (Thorlabs, S1013S), and a polarization controller, PC_2. Branch III contains only a polarization controller, PC_3. Note that the branch has no SOA due to the limited number of SOAs available during the time of our experiment. All the three branches, I, II and III, are connected by two 3dB fiber couplers, C_1 and C_2. Each 3dB fiber coupler, C_1 and C_2, is also connected to a Sagnac loop mirror, SLM_1 and SLM_2, respectively as shown in Fig. 1. These Sagnac loop mirrors with a polarization controller placed in each loop act as variable reflectors. By adjusting the polarization controller (i.e., PC_4 or PC_5), one can change the reflectivity of the loop mirrors and thereby, can switch from single to dual-output port configuration. The low power tunable optical filter (TF), which is placed in the common branch I, is used for selecting and tuning the operating wavelength of the proposed fiber laser.

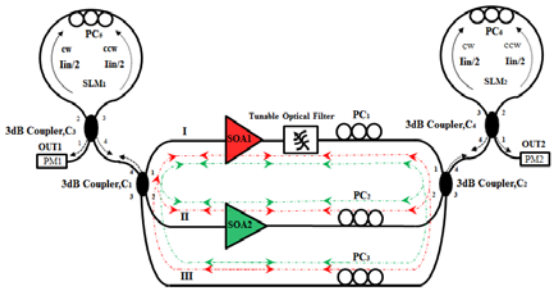

Figure 1: Experimental setup of the dual Sagnac loop mirror SOA- based tunable fiber compound-ring laser.

3 PRINCIPLE OF OPERATION

When the pump level (i.e., bias current threshold level) of either SOA is more than the total fiber compound-ring cavity losses, amplified spontaneous emission (ASE) emitted from SOAs either propagates in the forward and backward directions. For instance, when a bias current I_B of around 75 mA) is injected into the SOA_1 (branch I), the emitted ASE emitted by the SOA_1 (branch I) circulates in clockwise (cw) direction by propagating through a tunable optical filter, which selects a passband of certain wavelengths. The selected wavelengths reach a 3dB fiber coupler C_2 after propagating through a polarization controller, PC_1. Then, the selected light beam that arrives at port 1 of the 3dB fiber coupler C_2, is equally split into two branches, II and III at port 2 and port 3, respectively. The light beam that circulates into branch II propagates through a polarization controller, PC_2, before it is amplified by SOA_2 when its bias current level I_B is around 180 mA. Then, the amplified light beam arrives at port 2 of the 3dB fiber coupler C_1 where it is equally divided between port 1 and port 4. Similarly, light beam from Branch III reaches port 3 after passing through a polarization controller, PC_3. A half of the light beam coupled into port 1 of the 3dB fiber coupler C_1 is further amplified by SOA_1. Thus, a round-trip is completed in the fiber compound-ring structure and allows lasing to occur. Furthermore, the remaining 50% of the light beam is coupled into the output port 4 of the 3dB fiber coupler C_1 is injected into the input port 4 (i.e., I_{in}) of the Sagnac loop mirror, SLM_1. The polarization controller, PC_4, controls the reflectivity of the SLM_1 and it is achieved by adjusting the state of polarization of the light beams propagating through the loop mirror. For a single output port configuration, the polarization controller PC_4 of SLM_1 is adjusted for minimum power at the output port 1 (OUT1). The counter-clockwise and clockwise light beams interfere destructively at the output port 1 while interfere constructively at the port 4 of the 3dB fiber coupler, C_3, and thus it channels all the power back to the compound-ring cavity.

As there is no optical isolator placed in any of the three branches of the fiber compound-ring resonator, the two counter-propagating light beams circulate in the nested ring cavities as shown in Fig. 1. The counter-clockwise (ccw) propagating beam from the SOA_1 reaches the port 1 of the 3dB coupler C_1, splits into two equal light beams (i.e., 50%) and is transmitted into the ports 2 and 3. The light beam that propagates into branch II undergoes amplification by SOA_2. The amplified light beam that takes the path of branch II passes through a polarization controller PC_2 before it reaches port 2 of the 3dB fiber coupler C_2, while the light beam that propagates through the branch III passes through the polarization controller PC_3 before it reaches port 3 of the 3 dB fiber coupler C_2. Half of the light beam at the 3 dB fiber coupler C_2 is coupled into port 1 where it propagates back into branch I to complete one round trip, while the other half of the beam is channelled into SLM_2. Similarly, the light beam that is fed into the SLM_2 exits at the output port 1 of the 3dB fiber coupler C_4 (OUT2). The polarization controller, PC_5, can control the output power. An optical spectrum analyzer (OSA), variable optical attenuator (VOA) and optical power meter (PM) were used to characterize the proposed fiber compound-ring laser. Note that the path lengths of both loops are the same since all branches have identical length and all fiber connections are done by using FC/APC connectors.

4 CHARACTERIZATION OF THE FIBER RING LASER

4.1 Gain Media

The amplified spontaneous emission (ASE) of SOA_1, and SOA_2 were characterized by using an optical spectrum analyzer (OSA) where both SOAs were set at the same bias current (I_B) of 200 mA. Even though all two SOAs are biased at the same current level of 200 mA, they exhibited different ASE spectra where SOA_1 has higher gain than SOA_2

for the same bias current level. Thus, different bias current levels are required in order to get the same output power when the SOAs are individually used in the proposed fiber compound- ring resonator.

4.2 Output Power and FWHM

Maximum and minimum insertion losses (IL) of 5.5 dB 2.2 dB were measured at 1520 nm and 1570 nm, respectively. Similar downward trend was also noticed in the FWHM linewidths, which varies from 0.4 to 0.32 nm at 1520 and 1570 nm, respectively.

Due to the downward trend of the insertion losses from the tunable filter, an upward trend is also expected in the output power of the proposed fiber compound-ring laser for a constant gain setting of the SOAs. Consequently, a constant output power can be obtained over the entire wavelength tuning range by adjusting the bias current (I_B) of the SOAs but at the expense of signal broadening of the fiber laser source.

The reflectivity of both SLMs was set at less than 0.1% so that both output ports of the fiber compound-ring lasers (i.e., OUT1 and OUT2) have the same output power. Then, by collecting both clockwise and counter-clockwise propagating light beams through the SLM_1 and SLM_2, respectively, we measured the 3dB bandwidth at different bias current levels at 1550 nm wavelength by using an OSA. The 3dB-bandwidth increased from 0.1985 to 0.2182 nm as the bias current was increased to the standard bias current of each of the SOAs (Table 1).

Table 1: 3dB-bandwidth (FWHM) at different bias current I_B (mA) at 1550 nm wavelength with both Sagnac loop mirror reflectivity set at <0.1%.

SOA_1 I_{B1} (mA)	SOA_2 I_{B2} (mA)	P_{OUT1} (dBm)	P_{OUT2} (dBm)	FWHM (nm)
75	250	3.40	3.40	0.1985
100	300	5.80	5.70	0.2075
125	350	6.73	6.75	0.2122
150	400	7.65	7.68	0.2131
175	450	8.35	8.35	0.2157
200	500	8.94	8.95	0.2182

4.3 Coherent Beam Combining Efficiency

The principle of the proposed passive coherent beam combining technique of two compound-ring based fiber lasers with two adjustable output couplers (i.e., Sagnac loop mirrors) is based on passive phase-locking mechanism due to spontaneous self-organization operation (Bruesselbach et al., 2005). Due to wide bandwidth of the SOAs, the passive phase-locking mechanism allows the fields' self-adjustment to select common oscillating modes or resonant frequencies of the counter-propagating (i.e., clockwise and counter-clockwise) light beams in the two merged ring cavities and optimize their in-phase locking state conditions without any active phase modulating system.

In order to determine the beam combining efficiency of the proposed fiber laser structure, we first used each individual SOA as gain medium in the common branch I of the compound-ring cavity and measured the output power produced by the fiber laser system at its both output couplers, OUT1 and OUT2. Then, we placed at the same time both SOAs, SOA_1 (Kamelian model) and SOA_2 (Thorlabs, S1013S), in the compound-ring cavities (branch I and II, respectively). Similarly, we measured the output power delivered at both output couplers of the proposed fiber laser. Note that the reflectivity of the Sagnac loop mirrors, SLM_1 and SLM_2, was adjusted to maximum (i.e. > 99.9 %) and minimum (i.e., < 0.1%), respectively. The tunable filter was manually adjusted from 1535 to 1565 nm and each semiconductor optical amplifier, SOA_1 and SOA_2, was driven and kept constant at its standard bias current, 200 and 500 mA, respectively. Fig. 2 illustrates the passive coherent beam combining efficiency spectrum (right vertical axis) and the output power spectrum (left vertical axis) from the proposed fiber compound fiber –ring laser operating with individual SOAs as well as both SOAs over the C-band tuning range of 30 nm.

The beam combining efficiency (filled circles) was obtained by dividing the optical power measured at the output port (OUT2) when the fiber laser was operating with both SOAs by the power summation (unfilled triangles) of the same output port of the fiber laser while operating with individual SOA, SOA_1 (filled squares) and SOA_2 (unfilled circles). The leakage optical power spectrum (unbroken line crosses) at the other output port (OUT_1) remained below -28.5 dBm. The maximum output power delivered by the fiber laser operating with a single SOA, SOA_1 (Kamelian model) and SOA_2 (Thorlabs model), was +8.91 and +8.90 dBm at 1565 nm, respectively. On the other hand, when both SOAs were placed in the compound-ring cavities, the maximum measured output power (broken line crosses) obtained at the output port, OUT2, was + 11.9 dBm at 1565 nm, which is almost double of the output power obtained with either individual SOA placed in the fiber compound-ring laser cavity. Moreover, the maximum output power obtained by just adding the optical power (triangles) from single SOA fiber laser operation at the output port, OUT2, was +11.91 dBm vs. +11.90 dBm measured output power from the fiber laser operating with both SOAs at 1565 nm wavelength. This is where the insertion losses of the tunable filter were the lowest.

The maximum and minimum obtained combining efficiency (filled circles) was 99.76% and 98.06 % at 1565 nm and 1555nm, respectively, as shown in Fig.5 (right vertical axis).

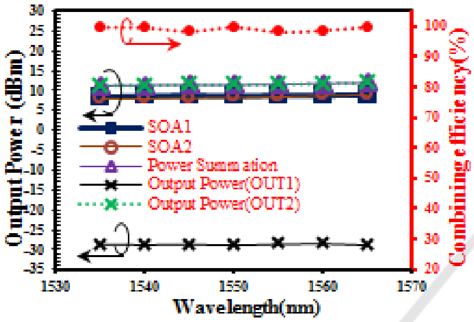

Figure 2: Shows individual SOA output power spectrum: SOA_1 (filled squares), SOA_2 (unfilled circles), output power summation spectrum of both SOAs (unfilled triangles), and actual measured output power (crosses) at the output port , OUT2 with SOA_1 and SOA_2 driven at 200 mA and 500 mA constant bias current. The PC_1 and PC_2 were maximized for each wavelength.

4.4 Fiber Laser Power Tunability and Its Switchable Dual-Output Power Operation

The proposed fiber compound-ring laser has a feature of operating with two adjustable and switchable output ports (i.e., OUT1 and OUT2). The output power from either output port can be tuned by adjusting the gain of the semiconductor amplifiers, SOA_1 and SOA_2, by controlling their bias current levels (see Table 1) or by adjusting the reflectivity of the Sagnac loop mirrors, SLM_1 and SLM_2, while keeping the former constant. The latter approach involves the adjustment of the reflectivity of both Sagnac loop mirrors, SLM_1 and SLM_2 while keeping the gain of both SOAs constant (i.e., I_{B1} and I_{B2} set at 200 and 500 mA, respectively). Thus, the proposed fiber compound-ring laser can be operated in single or dual-output configuration depending on the reflectivity of the SLM1 and SLM_2. In single output configuration, one of the Sagnac loop mirror, SLM_1 or SLM_2, should be kept at high reflectivity (i.e., $\geq$ 99.9%) by adjusting its polarization controller, PC_4 or PC_5, respectively, while keeping the other Sagnac loop mirror at its lowest reflectivity of $\leq$ 0.1%.

The tunable filter was set at 1550 nm wavelength in order to characterize the power tunability performance of both output ports of the fiber laser. Then, we initialized the reflectivity settings of the SLM_1 and SLM_2 to $\leq$ 0.1% and $\geq$ 99.9%, respectively. The initial measured output power from both output ports, OUT1 and OUT2 was +11.85 dBm and -28.9 dBm, respectively. Moreover, we gradually adjusted the reflectivity of the Sagnac loop mirror, SLM_1, by slowly changing the polarization state of the counter-propagating light beams into the SLM_1 by adjusting the polarization controller, PC_4, while recording the power meter readings and the output signal spectrum at both output ports, OUT1 and the FWHM at output port, OUT1. We were able to control the output power from the output port, OUT1, from +11.85 dBm to -28.5 dBm while keeping OUT2, at -28.9 dBm by also optimizing the polarization controller, PC_5, of SLM_2. Similarly, we also set the reflectivity of SLM_1 and SLM_2 to $\geq$ 99.9% and $\leq$ 0.1%, respectively, and checked both output ports' performance in the similar manner as stated above, where the measured output power from output port, OUT_2 was adjusted from +11.87 dBm to -28.9 dBm while keeping the output port, OUT1, at -28.9 dBm. Fig.6 illustrates the output power from both output ports, OUT1 (unfilled squares) and OUT2 (unfilled circles) as a function of the reflectivity of the SLM_1 and SLM_2, respectively. Note that both output port behave similarly and the 3dB-bandwidth of the light beam from OUT1 (filled triangles) and OUT2 (filled circles) increased as the reflectivity of the Sagnac loop mirrors increased while the output power decreased as shown in Fig.3, due to the strong feedback (i.e., reflected light beam) from each SLMs.

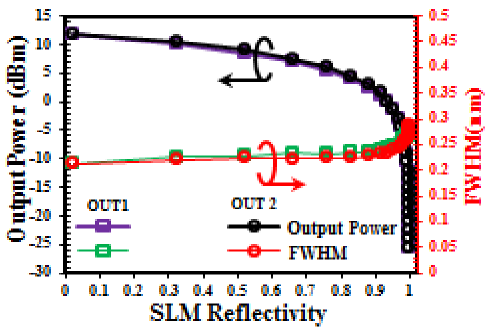

Figure 3: Shows the output power and the 3-dB-bandwidth from both output ports, OUT1 (unfilled squares) and OUT2 (unfilled circles) as a function of different reflectivity values of the Sagnac loop mirrors for single output port operation.

Fig. 4 shows the output power from the two output ports of the proposed fiber laser. In dual-output port configuration, both output ports can be fixed and adjusted to any output power between +11.9 and -28.9 dBm. We firstly set both output ports, OUT1 and OUT2, to +8.94 and +8.95dBm by adjusting the reflectivity of both Sagnac loop mirrors, SLM_1 and SLM_2 at ≤ 0.1%, as shown in Fig.4. Then, we gradually tuned the output power from the output port, OUT1, from +8.94 to -28.9 dBm by adjusting the reflectivity of the SLM_1 from 0.1% to more than 99.9% while optimizing the reflectivity of the SLM_2 in order to keep the output power at OUT2 constant at +8.95 dBm. The reflectivity of the SLM_2 was around 50% when the one of the SLM_1 was around 99.9% in order to maintain the output power at OUT2 constant at +8.95 dBm.

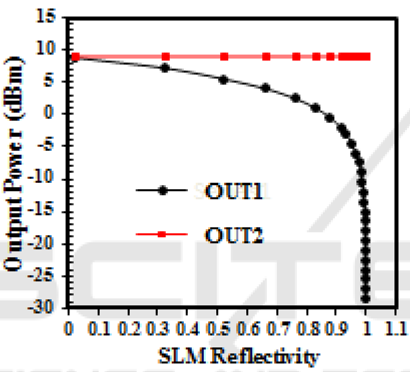

Figure 4: Illustrates the output power from both output ports, OUT1 (filled circles) and OUT2 (unfilled squares) for different reflectivity values of the Sagnac loop mirror, SLM_1 for dual-output port operation while keeping output power at OUT2 constant at +8.95 dBm.

4.5 Wavelength Tunability and Power Stability

The wavelength tuning range of the optical filter that was used in the proposed fiber laser has 50 nm. Its maximum IL is 5.5 dB at 1520 nm and its minimum IL is 2.2 dB at 1570 nm. Fig.5 shows the fiber laser wavelength-tuning spectrum.

We first set the bias current for both SOAs at 200 and 500 mA, for SOA_1 and SOA_2, respectively. The reflectivity of the SLM_1 and SLM_2 were set and kept constant at ≤ 0.1% and ≥ 99.9%, respectively. Then, the wavelength of the output light beam was measured with an OSA, and was tuned by manually adjusting the tunable filter, from 1535 to 1565 nm while optimizing the polarization controllers, PC_1, PC_2 and PC_3, at each wavelength of 1535, 1540, 1545, 1550, 1555, 1560 and 1565 nm as illustrated in Fig.8. The peak signals from the measured output wavelength spectra by using an optical spectrum analyzer were used to determine the optical signal-to-noise ratio (OSNR) of the proposed fiber compound-ring laser. We subtracted the peak power value at each center wavelength from the background noise level of each wavelength spectrum. The OSNR remained well above +39 dB over the whole wavelength tuning range, where the maximum OSNR of +44.6dB was obtained at 1565nm.

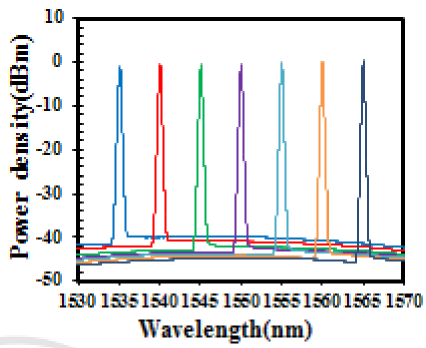

Figure 5: Shows the wavelength spectrum of the fiber compound-ring laser where PC_1, PC_2 and PC_3, were optimized at each wavelength.

We finally performed short-term optical power stability test at room temperature with SOA_1, and SOA_2 set at the standard bias current levels of 200 and 500 mA, respectively, while the tunable filter was set and kept fixed at 1550 nm central wavelength. The OSA was also used to monitor and acquire the data. The optical stability test was carried out over a course of 180 minutes with time interval of 1 minute, and OSA resolution bandwidth of 0.01 nm without additional data averaging. The power stability measurements with fluctuations of less than ±0.02 dB were measured, which indicates that the proposed fiber compound-ring laser is very stable. The power fluctuations during the stability measurement can be minimized by properly packaging the proposed fiber compound-ring laser system.

5 CONCLUSION

We successfully demonstrated very high coherent beam combining efficiency of two SOAs used as gain media in all-single-mode fiber compound-ring cavities with two switchable and power adjustable output couplers formed by using two Sagnac loop mirrors. Due to the advanced technologies of semiconductor optical amplifiers and tunable filters covering wide range of wavelength spectrum in different electromagnetic spectrum bands, the proposed fiber compound-ring laser can be used to build compact laser systems covering different optical wavelength-bands.

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