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Simeon Bikorimana
CUNY City College

Muhammad A. Ummy
CUNY New York City College of Technology

Abdullah Hossain
CUNY City College

Richard Lin
CUNY New York City College of Technology

Roger Dorsinville
CUNY City College

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Characterization of a Sagnac Loop Mirror-Based Hybrid Passive Variable Optical Coupler/Attenuator

Simeon Bikorimana[a], Muhammad A. Ummy[b], Abdullah Hossain[a], Richard Lin [b], and Roger Dorsinville[a]

[a]Department of Electrical Engineering, The City College of City University of New York
160 Convent Avenue, New York, NY 10031, USA
[b]Department of Electrical and Telecommunications Engineering Technology
New York City College of Technology of City University of New York
186 Jay Street, Brooklyn, NY 11201, USA

ABSTRACT

The implementation and performance of a unidirectional all-single mode fiber hybrid passive variable optical coupler/attenuator based on a Sagnac loop mirror with a continuous variable coupling ratio using off-the-shelf optical sub-components are discussed. Parameters of two output ports of the unidirectional hybrid passive variable optical coupler/attenuator, such as maximum coupling ratio, insertion loss, excess loss, and wavelength-dependent return loss over the C-band at room temperature are reported. The reflectivity of the Sagnac loop mirror continuously varies from 0.1% to 99.9% by adjusting retarders of a polarization controller. The 3-dB coupling ratio (i.e., 50:50) between the two output ports of the hybrid passive variable optical coupler/attenuator is achieved when the reflectivity of the Sagnac loop mirror is set at 73%. The attenuation and coupling ratio range of 1.7 - 45.5 dB and 0.13 - 99.87% is achieved, respectively, from the implemented unidirectional hybrid passive variable optical coupler/attenuator. The availability of the off-the-shelf optical sub-components and achieved easy control of continuous variable coupling ratio makes the proposed unidirectional hybrid passive variable optical coupler/attenuator a cost-effective optical device for several applications including optical system testing, and general laboratory experiments.

Keywords: Sagnac interferometer, variable optical attenuator, fiber coupler, fiber loop mirror, polarization controller, fiber optics and optical communications, optical design and fabrication

1. INTRODUCTION

Optical power adjustment capability is usually necessary during the fiber optical system testing and normal working process, as well as general optical laboratory experiments to precisely attenuate and balance the optical signal strength as the optical signal travels through the fiber circuit system. It is commonly needed to adjust the optical signal intensity after an optical source, especially, lasers, before and after an optical amplifier, and prior a photo-detector or receiver. Hence, attenuation and splitting/coupling of the optical signal intensity in optical telecommunication networks, such as passive optical networks(PONs), fiber-to-the-home (FTTH), and cable TV networks is usually achieved by using passive all-fiber variable optical attenuators(VOAs), as overloading protecting devices,[1] and variable optical couplers (VOCs) as optical signal splitter/combiner devices.[2]

Wavelength independent VOAs enable the control of the optical signal intensity of individual optical channels (i.e., wavelengths) in wavelength division multiplexing (WDM) systems, thus, making them a key element in reconfigurable optical add-drop multiplexers (ROADMs).[3–5] Various processes and techniques are used to

Further author information: (Send correspondence to Simeon Bikorimana)
Simeon Bikorimana: E-mail: sbikorimana@ccny.cumy.edu, Telephone: +1 (212) 650 7293
Muhammad A. Ummy: E-mail: maummy@citytech.cuny.edu, Telephone: +1 (718) 260 4948
Abdullah Hossain: E-mail: ahossai12@citymail.cuny.edu, Telephone: +1 (212) 650 7293
Richard Lin: E-mail: richard.lin2@mail.citytech.cuny.edu
Roger Dorsinville: E-mail: rdorsinville@ccny.cuny.edu, Telephone: +1 (212) 650 6685

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fabricate VOCs such as mechanical polishing,[6] micro-mechanical systems, fused bi-conic taper,[7–10] and thermo-optic effects.[11] Moreover, several methods are also used to manufacture VOAs such as liquid crystal,[12–15] fiber displacement,[16] light blocking,[17] cladding refractive index modification,[18] and absorbing micro-fluid. The aforementioned fabrication processes can result in sophisticated accurate devices[19–23]that are expensive but not feasible to utilize all the time whenever a particular slitting ratio or attenuation level is needed on the-fly during the optical system testing process or general optical laboratory experiments. Therefore, in order to build a cost-effective VOC or VCA device, the off-the-shelf optical sub-components should be mainly considered.

This work discusses how to design, build, and characterize a unidirectional Sagnac loop mirror-based hybrid passive variable optical coupler/attenuator which consists of the off-the-shelf passive optical sub-components. The proposed device can function as a variable optical splitter or variable optical attenuator depending on how many of its output ports are enabled. Disabling an output port by simply placing an optical absorber/ beam dump at that port will force the proposed device to operate as a VOA while enabling both ports, port A and port B, results in the unidirectional variable optical coupler operation. The performance metrics associated with the unidirectional VOC system such as maximum coupling ratio, insertion loss, excess loss, and 3-dB coupling setting are presented and analyzed. Wavelength-dependent loss, minimum and maximum attenuation levels, and dynamic attenuation range parameters associated with the VOA operation are also discussed. Briefly, the 3-dB coupling ratio (i.e., 50:50) between the two output ports of the unidirectional hybrid passive variable optical coupler/attenuator is achieved when the reflectivity of the Sagnac loop mirror is set at 73%. The attenuation and coupling ratio range of 1.7 - 45.5 dB and 0.13 - 99.87% is achieved, respectively, from the implemented unidirectional hybrid passive variable optical coupler/attenuator.

2. EXPERIMENTAL SETUP AND PRINCIPLE OF OPERATION

The proposed hybrid passive variable optical coupler/attenuator is implemented by splicing a single-mode fiber optical circulator (OC) and a fiber-optic Sagnac loop mirror, as shown in Fig.1. The optical beam emitted by the tunable fiber laser enters the polarization-independent circulator via port 1 and exits via port 2. After exiting port 2, it enters the 3-dB coupler of the Sagnac loop mirror (SLM) through port 4 and equally splits into two beams, noted as I_1 and I_2. The I_1 beam exits ports 3 while the I_2 beam exits port 2 of the 3-dB coupler. The two beams, I_1 and I_2, counter propagate through the SLM whose reflectivity is controlled by manually adjusting the wave-retarders of the polarization controller (PC). The I_1 beam traverses the fiber loop of the SLM in the clockwise direction, and then enters port 2 of the 3-dB coupler.

On the other hand, the I_2 beam circulates in the counter-clockwise direction along the fiber loop of the SLM and enters port 3 of the 3-dB coupler. Both I_1 and I_2 pass through the PC of the SLM before reaching port 2 and port 3 of the 3-dB coupler, respectively. Then, both counter-propagating beams, I_1 and I_2, interfere in the 3-dB coupler depending on their state of polarization. The portion of the coupled beams into port 4 and port 1 of the 3-dB coupler depends on the reflectivity of the SLM. Note that port 1 of the 3-dB coupler leads to the output port A of the system. The beam that exits port 4 of the 3-dB coupler travels in the opposite direction of the incoming beam that exits port 2 of the optical circulator. Furthermore, the reflected beam from the SLM enters port 2 of the optical circulator and then exits from port 3, which leads to the output port B of the system.

The primary mechanism by which the proposed Sagnac loop mirror-based hybrid passive variable coupler/attenuator operates is by controlling the SLM reflectivity (i.e., via manual adjustment of the PC). The reflectivity can be set to any value between a minimum ($< 0.1\%$), and maximum ($> 99.9\%$) value. When both output ports are enabled, for the unidirectional variable optical coupler (VOC) operation, increasing the SLM reflectivity results in reflecting more optical power of the beam from port 4 of the SLM into the optical circulator while decreasing the optical power of the beam exiting at port 1 (i.e., output port A). On the contrary, the decrement of the SLM reflectivity results in directing more optical power of the beam that exits the SLM at port 1 of the 3-dB coupler (i.e., output port A) while less optical power is reflected to port 2 of the optical circulator, hence, less optical power at the output port B (i.e., port 3 of the OC).

It is through the above mechanism by which the coupling ratio between output ports, A and B, is continuously varied at any desirable coupling ratio. By disabling either of the output ports results in the proposed system to operate as a passive variable optical attenuator (VOA). Moreover, by adjusting the reflectivity of the SLM, the

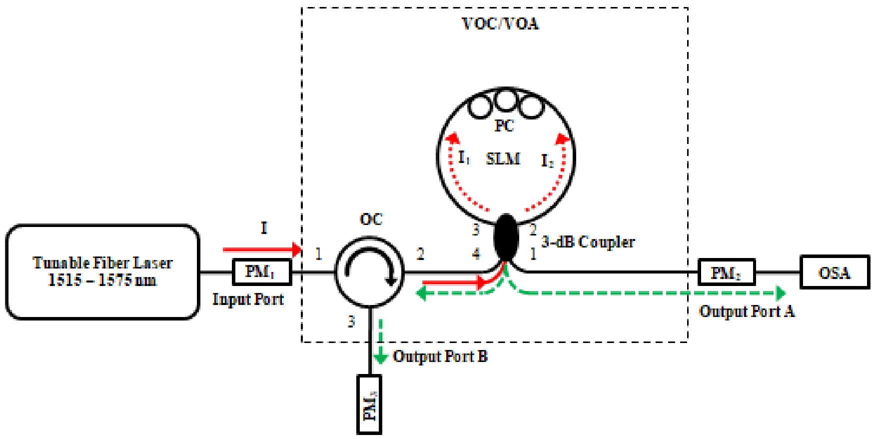

Figure 1. Experimental setup of a unidirectional all-single mode fiber hybrid passive variable optical coupler/attenuator.

attenuation level is varied at the active output port (i.e., either A or B). Hence, the proposed system consists of two primary operating configurations as a unidirectional variable optical coupler and a variable optical attenuator. Inline power meters (Eigen Light 420 WDM Power Monitor-Attenuator), PM_1 and PM_2, were utilized to monitor the input and output power. PM_1 was inserted between the fiber laser and optical circulator to monitor the input power, and PM_2 was inserted between the SLM (i.e., output port A) and the optical spectrum analyzer (OSA). Moreover, a power meter (Thorlabs PM100D), PM_3, was connected to port 3 of the OC to monitor the output power level at the output port B of the proposed system. Below, the unidirectional VOC configuration is firstly assessed, and then the analysis of both VOA systems, VOA_A and VOA_B, follows.

3. RESULTS AND ANALYSIS

3.1 Variable Optical Coupler Configuration

The VOC parameters (maximum coupling ratio, insertion loss, excess loss, and 3 dB coupling setting) were determined according to the experimental setup, as shown in Fig. 1; note that both output ports A and B are active. Similarly, to monitor the output power level, an inline power meter was inserted between output port A and an optical spectrum analyzer (OSA).

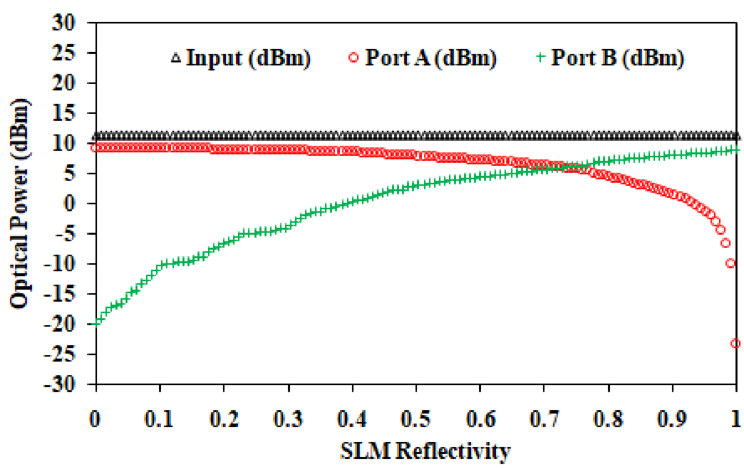

Figure 2. Illustrates input power(triangle) and output power of port A (circles) and B (crosses), respectively, as a function of the SLM reflectivity for the unidirectional VOC operation at 1550 nm wavelength.

The input signal from the tunable laser source was fixed at 1550 nm wavelength and optical input power of 11.4 dBm. The PC was manually adjusted to gradually increase the SLM reflectivity from minimum reflectivity ($< 0.1\%$) to maximum reflectivity ($> 99.9\%$) while recording the output power levels at ports A and B, as demonstrated in Fig.2. At the minimum reflectivity setting, the output power of port A was 9.06 dBm while the output power of port B was -19.86 dBm. Also, as the SLM reflectivity was swept from minimum to maximum, the output power of port A decreased from 9.06 dBm to -23.26 dBm while the output power at port B increased from -19.86 dBm to 8.75 dBm. The 3-dB coupling ratio was achieved at 73% SLM reflectivity, where both output port power levels were measured to be 6 dBm. In addition, the maximum coupling ratio of 0.13 - 99.87% was obtained at 1550 nm wavelength, as shown in Fig.3.

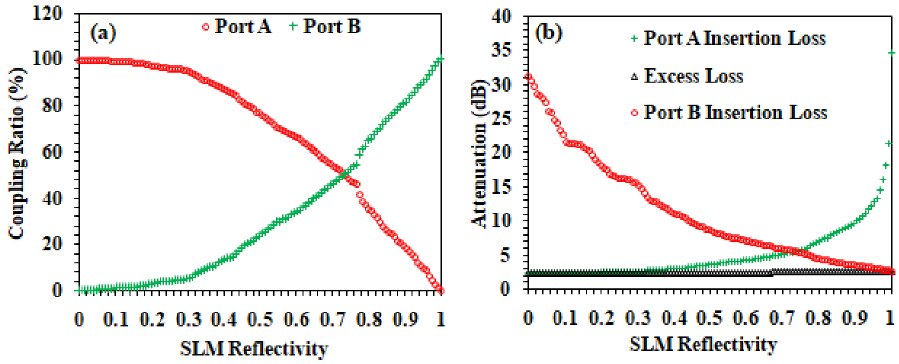

Figure 3. Illustrates the coupling ratio (a), and (b) shows insertion losses and excess loss of the output port A (circles), and port B (crosses) as a function of the SLM reflectivity of the unidirectional VOC operation at 1550 nm wavelength.

Table 1. VOC characterization summary at 1550 nm wavelength and 11.4 dBm input power.

Description	Port A	Port B
Maximum Power	9.06	8.75 dBm
Minimum Power	-23.26 dBm	-19.86 dBm
Maximum Attenuation	34.68 dB	31.27 dBm
Minimum Attenuation	2.34 dB	3.65 dB
Attenuation Range	32.34 dB	27.62 dB
3-dB Coupling	SLM Reflectivity = 73%	
Minimum Excess Loss	2.34 dB	
Maximum Excess Loss	2.65 dB	
Maximum Coupling Ratio	0.13 - 99.87%	

The excess loss of the variable optical coupler, which is majorly resultant from the intrinsic losses associated with the optical circulator and 3-dB coupler, remained between 2.35 dB and 2.65 dB ($\pm$ 0.3 dB). Besides, the lowest insertion loss at any output port corresponds to the highest coupling ratio at that specific output port. On the other hand, the highest insertion loss at any output port corresponds to the lowest coupling ratio at that specific port, as well. This is clearly observed when comparing Fig.3 (a) and Fig.3 (b) together. Also, Table 1 above provides a reference for the summary of the experimental results.

3.2 Variable Optical Attenuator Configuration

One of the two output ports, A and B, of the proposed system can be used as the main output port, VOA_A, or VOA_B, respectively. A beam dump (i.e., an optical absorber) was placed at port B, as shown in Fig.5 (a), and port A (See Fig.5 (b)) to achieve the attenuation configuration. The following parameters were determined for each activated port: wavelength-dependent losses, minimum and maximum attenuation levels, and attenuation range. The characterization of the VOA_A configuration involves the insertion of inline power meters (Eigen Light 420 WDM Power Monitor-Attenuator) at both the input and output port; one inline power meter was placed at the optical circulator port 1, and the other one was placed at the VOA port A, respectively) and it was terminated at an OSA for wavelength monitoring purposes.

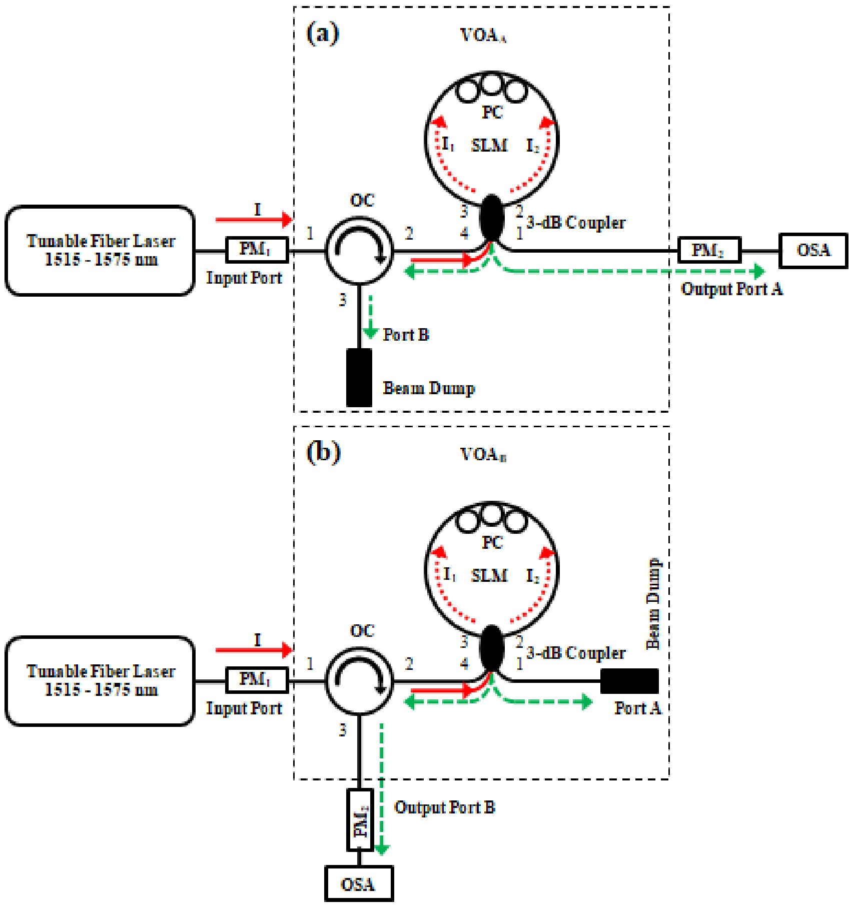

Figure 4. (a) and (b) shows the attenuation configuration of the VOA utilizing port A and port B, respectively, as an output port.

For the proper assessment of all VOA-parameters, the fiber laser was kept at a constant optical power of 10.7 dBm. The first parameter to be evaluated was the wavelength-dependent loss response at several attenuation levels over the fiber laser tuning range of 50 nm, from 1521 nm to 1571 nm. The SLM reflectivity was initially set to minimum reflectivity ($< 0.1\%$) to obtain the minimum attenuation level at the starting testing point, 1521 nm wavelength. Then, the tunable fiber laser source wavelength was tuned in 1 nm increments from 1521 nm to 1571 nm, and the optical output power of port A was recorded (See Fig.5. (a)). Several wavelength-dependent loss levels were recorded, see Fig.7. The attenuation level was increased by manually adjusting the polarization controller. This process was repeated until the maximum SLM reflectivity at 1521 nm was obtained for an attenuation level of 37.5 dB.

The minimum and maximum attenuation levels of 1.7 dB and 45.5 dB were obtained at 1566 nm and 1532 nm, respectively. Thus, the maximum attenuation dynamic range of 43 dB was achieved at 1532 nm. Table 2 is a comprehensive summary of the VOA_A system characteristics of port A in the attenuation configuration.

Table 2. Port A, VOA_A, characterization summary, and 10.7 dBm input power in the attenuation configuration.

Insertion Loss	2 dB at 1550 nm
Maximum output power	9 dBm at 1566 nm
Minimum output power	-34.8 dBm at 1532 nm
Maximum Attenuation	45.5 dB at 1532 nm
Minimum Attenuation	1.7 dB at 1566 nm
Attenuation Range	43 dB at 1532 nm

In addition, port B of the VOA was characterized in the same manner as port A, as described above. Also, a beam dump was placed on port A of the VOA, as shown in Fig.4 (b). All tests and experimentation procedures performed on VOA_A were also conducted for the VOA_B, and their results are shown in Fig.5 (b). Table 3 also provides a comprehensive summary of the VOA_B system characteristics of port B in the attenuation configuration.

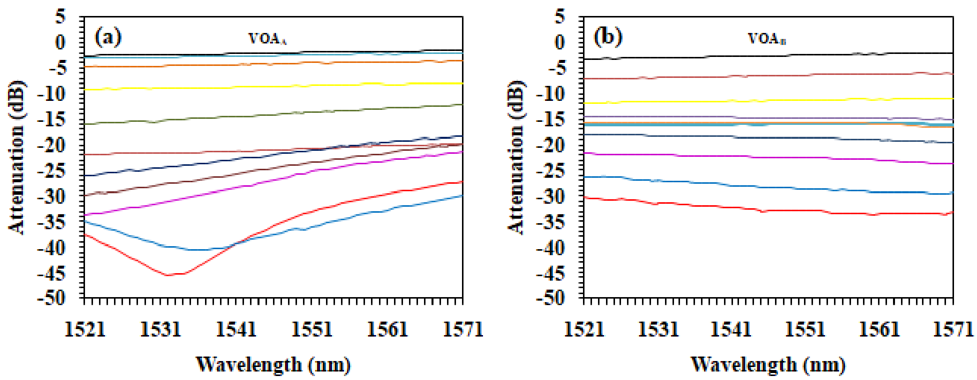

Figure 5. (a) and (b) shows wavelength-dependent losses of the VOA utilizing port A and port B, respectively, as an output port, in the attenuation configuration.

Minimum and maximum attenuation levels of 2.23 dB and 33.6 dB were obtained at 1566 nm and 1560 nm, respectively. The maximum attenuation range of 31.28 dB was achieved at 1560 nm. Finally, the insertion loss was measured to be 2.55 dB at 1550 nm, as shown in Table 3. Unlike the response of the VOA_B, the wavelength-dependent loss of the VOA_B maintained a flat response throughout the entire tuning range for all attenuation levels.

Table 3. Port B, VOA_B, characterization summary with 10.7 dBm input power in the attenuation configuration.

Insertion Loss	2.55 dB at 1550 nm
Maximum output power	8.47 dBm at 1566 nm
Minimum output power	-22.9 dBm at 1532 nm
Maximum Attenuation	33.6 dB at 1560 nm
Minimum Attenuation	2.23 dB at 1566 nm
Attenuation Range	31.28 dB at 1560 nm

4. CONCLUSION

The implementation method and performance of an all-single mode fiber hybrid passive variable optical coupler/attenuator with a continuous variable coupling ratio using off-the-shelf optical sub-components over the C-band are discussed. The proposed hybrid passive variable optical coupler/attenuator is implemented by splicing an optical circulator and a fiber-optic Sagnac loop mirror. The 3-dB coupling ratio of the hybrid passive variable optical coupler/attenuator was achieved when the reflectivity of the Sagnac loop mirror was set at 73%. The attenuation and coupling ratio range of 1.7 - 45.5 dB and 0.13 - 99.87% was achieved at 1550 nm, in the attenuation and coupling configuration, respectively, from the hybrid passive variable optical coupler/attenuator. Port A and port B in the attenuation configuration (VOA_A and VOA_B) exhibited attenuation range of 31 - 43 dB, respectively, with less than 2.55 dB insertion loss. Potential improvements to the proposed system, especially reduction of its insertion loss and size, include employing passive optical components with lower intrinsic losses as well as improving the packaging of the proposed system, such as eliminating lengthy fiber, fiber bends and loops to minimize unwanted sources of external attenuation.

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