Optical Quasi-Circulator Using Power Couplers and Optical Amplifiers

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***Abstract*—A new concept for an optical quasi-circulator operating in the 1550-nm band is proposed and experimentally demonstrated in this letter. The quasi-circulator consists of two power couplers, two optical amplifiers, and a pair of attenuators. The power splitters are connected back-to-back and have a high split ratio of 98 : 2. The amplifiers are used as directional devices to block reverse energy flow from Port 2 to Port 1 as well as from Port 3 to Port 2 in the quasi-circulator. The attenuators are used for overall system gain control. Measurements show an insertion loss close to 0 dB in the forward directions from Port 1 to Port 2 and from Port 2 to Port 3.**

***Index Terms*—Active circulator, optical circulator, optical quasi-circulator, photonic integrated circuits (PICs).**

I. Introduction

To further increase the ability of photonic integrated circuits (PICs) to carry out complex signal processing tasks, it is necessary to realize as many optical components on-chip as possible. Compared to active components such as lasers, amplifiers, and modulators, passive components are generally more amenable to high levels of integration because usually they can be implemented using commmon materials such as silicon dioxide.

A set of passive components that have proved challenging to integrate on-chip, however, are isolators and circulators. Part of the difficulty stems from the fact that these directional devices rely on the phenomenon of Faraday rotation that is observed in anisotropic ferromagnetic compounds and such materials are not always compatible with PIC fabrication processes. Nevertheless, there have been a number of efforts to make directional devices such as isolators on-chip by using magnetooptic rib waveguides [1], [2] and semiconductor optical amplifier (SOA) waveguides that exhibit a nonreciprocal loss in the backward direction induced by a ferromagnetic layer [3], [4], [5], [6].

Quasi-circulators [7], [8] are closely related to circulators because both are three-port rotational devices with the only difference being that in a quasi-circulator there is no circulation from Port 3 to Port 1. In the majority of applications where circulators are found, a quasi-circulator can be used as well. In this letter, we present a new concept for a polarization-insensitive optical quasi-circulator without the use of ferromagnetic materials and that is suitable for on-chip realization. The quasi-circulator consists of two passive power splitters and two optical amplifiers plus a pair of attenuators for gain control. A proof-of-concept quasi-circulator was implemented using connectorized optical bench components. The experimental results show a wide operating bandwidth for the quasi-circulator and near-zero insertion loss.

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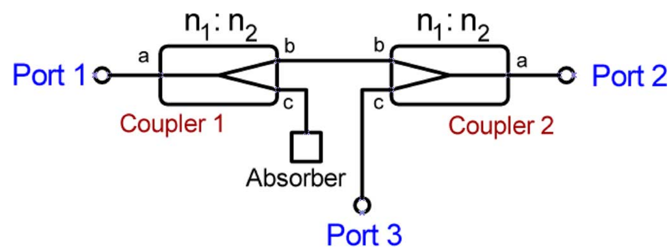

Fig. 1. Two identical back-to-back optical couplers.

II. Quasi-Circulator System Description

The basic building blocks of the quasi-circulator proposed in this letter are two power couplers connected back-to-back as shown in Fig. 1 and whose power split ratio is $n_1 : n_2$. The coupling factor between terminals a and b in each splitter is given by

$$k_1 = 10\log\left(\frac{n_1}{n_1+n_2}\right) \tag{1}$$

and if the splitters have the property that $n_1 \gg n_2$, then $k_1 \approx$ 0 dB and most of the light entering at Port 1 will emerge at Port 2 due to the reciprocal nature of the power couplers. On the other hand, the amount of energy appearing at Port 3 will be minimal because terminals b and c in the power splitters are well isolated from each other.

Since the system in Fig. 1 is completely passive, when a signal enters at Port 2 most of that energy will emerge at Port 1 and a small amount exits at Port 3. More precisely, the output power P_3 at Port 3 will be $P_3 = k_2 P_2$, where P_2 is the incident power and k_2 is the coupling factor between terminals a and c of the power splitter

$$k_2 = 10\log\left(\frac{n_2}{n_1+n_2}\right). \tag{2}$$

In a quasi-circulator, the energy incident at Port 2 should emerge at Port 3 instead of Port 1. By inserting two optical amplifiers

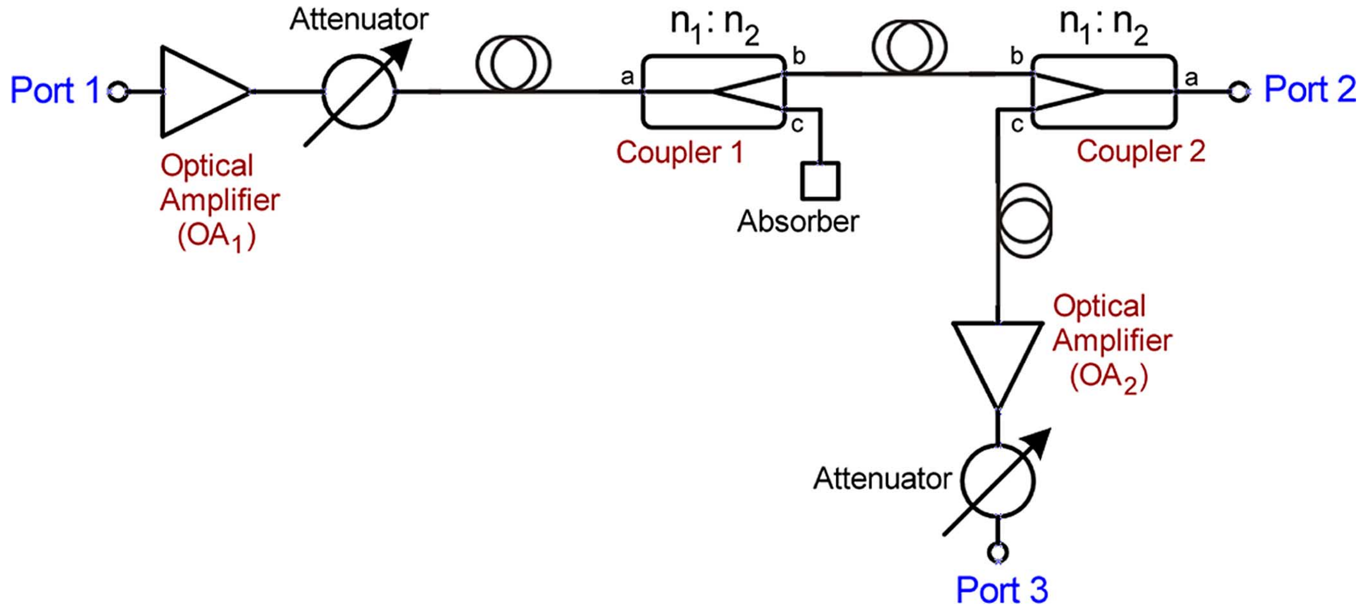

Fig. 2. Schematic diagram of the optical quasi-circulator.

(OA_1 and OA_2) into the foregoing system as shown in Fig. 2, the optical network can then function as a quasi-circulator.

In the new system, when light is incident at Port 2 that signal will enter OA_1 in the reverse direction and therefore a minimal amount of energy will appear at Port 1. If the gain G_2 of the second optical amplifier (OA_2) precisely compensates for the power coupling ratio given by (2), then $G_2 = 1/k_2$ and the output power at Port 3 will be $P_3 = G_2 k_2 P_2 = P_2$ as desired in a quasi-circulator.

In a full circulator, energy incident at Port 3 would appear at Port 1 and no energy would appear at Port 2. However, for the system depicted in Fig. 2, if a signal is applied at Port 3, then virtually no energy will appear at Port 1 because the signal sees amplifiers OA_2 and OA_1 in the reverse direction. For this reason, the optical network under discussion is more precisely labeled a "quasi-circulator," as noted earlier, which is consistent with the name given to analogous circuits in the microwave literature [9], [10] that show circulation between all the ports, except between Port 3 and Port 1.

The variable attenuators shown in Fig. 2 are used to accurately control the gain in the forward paths of the quasi-circulator in order to obtain the desired insertion loss, which is normally 0 dB, but in this system it could be greater than 0 dB since there is a certain amount of extra gain in the system.

III. Experimental Results

The optical quasi-circulator depicted in Fig. 2 was implemented using standard connectorized optical components in order to fully understand the behavior of the system prior to monolithic realization. Single-mode fibers were used to interconnect the components. Two identical optical amplifiers, model OAB1546 from JDSU, were used. The amplifiers had an operating wavelength range of 1540–1560 nm, a typical gain of 23 dB, and a saturated output power level of 17 dBm. HA017 attenuators from JDSU were employed and they had a variable attenuation range of 100 dB. The attenuators can tolerate a maximum input optical power level of 200 mW, or 23 dBm. The two optical power couplers used here were models DC202-S1 from Fitel and both had a coupling ratio of 98 : 2.

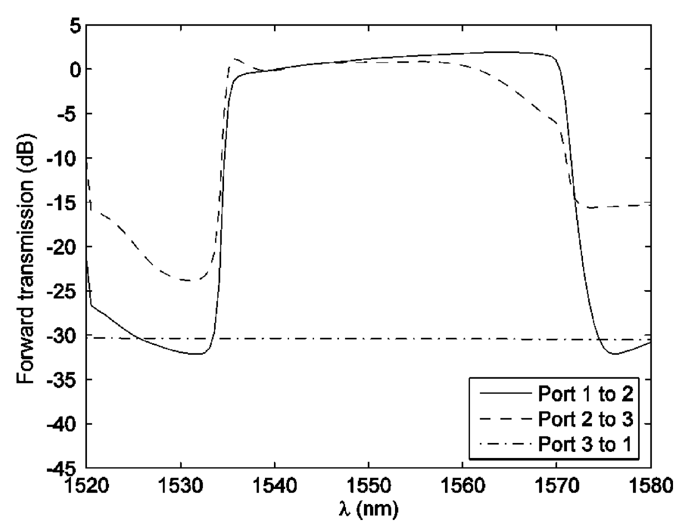

Fig. 3. Measured forward response of the quasi-circulator.

An Agilent 81600B tunable laser was used to produce the light beams and an Agilent 81634B optical power sensor was used to measure the forward and reverse transmission losses through the quasi-circulator. Measurements were taken at equally spaced points over the wavelength range from 1520 to 1580 nm.

Fig. 3 shows the measured forward transmission response of the optical quasi-circulator versus wavelength. The measured insertion loss from Port 1 to Port 2 is close to 0 dB and the insertion loss from Port 2 to Port 3 is also around 0 dB in the usable band of the quasi-circulator, which is established by the operating wavelength band of the optical amplifiers.

Since the power of the laser signal incident at Port 3 was 0 dBm and the power level detected at Port 1 was -31 dBm,

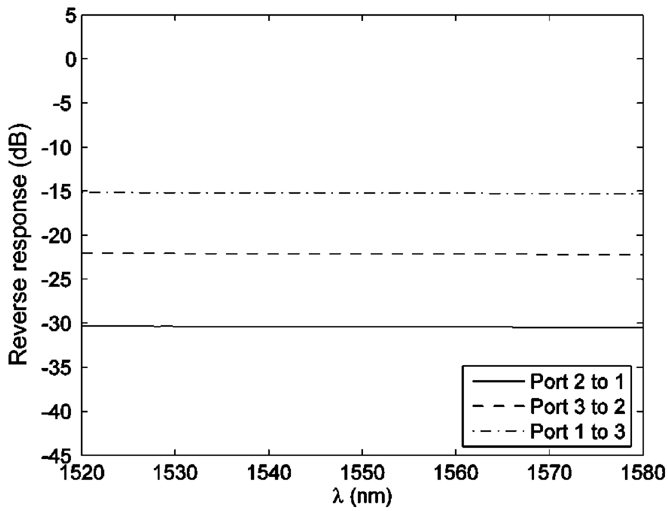

Fig. 4. Measured isolation between various ports of the quasi-circulator.

then the insertion loss between these ports is 31 dB. A high insertion loss was expected because the signal had to propagate in the reverse path of two optical amplifiers. The output power measured Port 1 was flat over the entire wavelength band because OA_1 in Fig. 2 produces a residual amount of light at its input port which is constant versus wavelength. This residual power comes primarily from the laser pump signal used in the amplifier.

The measured isolation between different ports of the quasi-circulator is plotted in Fig. 4. The isolation from Port 2 to Port 1 is 31 dB and the isolation from Port 3 to Port 2 is about 22 dB. The isolation between terminals b and c in Coupler 2 is around 65 dB and, therefore, it would make sense that the isolation between Ports 1 and 3 of the quasi-circulator should be quite high. However, the measurements on Fig. 4 show that the isolation between these ports is around 15 dB and not 65 dB. The reason for the low isolation between Ports 1 and 3 is attributed to residual energy emitted by OA_2 even when it has a very small or even no input light signal. The isolation between these two ports can be significantly improved by turning OFF OA_2 when there is no input signal at Port 2. From a practical point of view, one would need to sense if there is signal power at Port 2 using a power detector and the resulting information can be used to turn OA_2 ON or OFF, as needed. This feedback mechanism can be implemented with a power coupler, a diode power detector and some basic electronic circuitry.

The preceding results indicate that in a fully monolithic implementation of this quasi-circulator, careful attention must be paid to the design of the SOAs in order to minimize as much as possible their residual energy output since this affects the port-to-port isolations. Furthermore, it would be advantageous to also design the amplifiers to have a fast ON/OFF response to reduce the transient response if a feedback mechanism is used to control OA_2 as described above. The rest of the quasi-circulator components are passive elements whose performance can be accurately modeled prior to on-chip realization.

IV. Conclusion

An optical quasi-circulator has been experimentally demonstrated in this work which does not rely on Faraday rotation which, at the moment, is the most commmon way of implementing a circulator device at optical frequencies. The quasi-circulator has the potential for full monolithic optical integrated circuit implementation since it only relies on passive power splitters and optical amplifiers.

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