Non-Reciprocal Response in Heterogeneously Integrated Microdisks

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In this report, a novel concept for non-reciprocal behaviour in photonic integrated circuits is presented. Non-reciprocal devices are extremely useful for fully-functional photonic integrated circuits. Based on cross-gain suppression between the competing modes in the III-V microdisks integrated on silicon-on-insulator platform, unidirectional propagation of light has been predicted. Isolation numbers higher than 30 have been predicted in the simulations. The device is capable of operating in a unidirectional manner at low input power levels (upto 10s of microwatts) and thus can find use with heterogeneously integrated lasers (such as microdisks).

Introduction

Non-reciprocal devices are of paramount importance in optical communication systems and many applications such as prevention of optical feedback which causes destabilization of a laser source. At present, high quality devices are commercially available but only in the bulk form. All the proposed thin film devices, however, use the magneto-optic effect. Non-reciprocal response has also been expected in longitudinally non-uniform structures using nonlinear materials [1], alternatives to the use of Faraday effect for isolation can also be catered to by graded amplifying media [2] or quadratic waveguides which are asymmetric in the direction of propagation [3]. Use of interferometry to obtain non-reciprocal phase shifts has also been proposed for the design of such an isolator [4].

In this report, there is a numerical simulation result for an on-chip unidirectional propagation of light based on heterogeneously integrated microdisks coupled with straight waveguides. Integrated optical non-reciprocal devices can reduce cost and minimize size. The integration of III-V materials on silicon is also useful for adding other active functionalities on the photonic chip.

Non-Reciprocal Response in III-V Microdisks

As shown in fig. 1, a non-reciprocal behaviour is predicted in III-V microdisks integrated on silicon-on-insulator platform. High extinction between the forward and the backward propagating beams is possible in this design without any need for polarisers. The device relies on the gain-suppression effect to reduce the power carried by the one of the propagating modes in the microdisk. This device can be integrated on a chip to minimize the insertion loss and interconnection losses, but at the same time is wavelength-selective (only at resonance wavelengths).

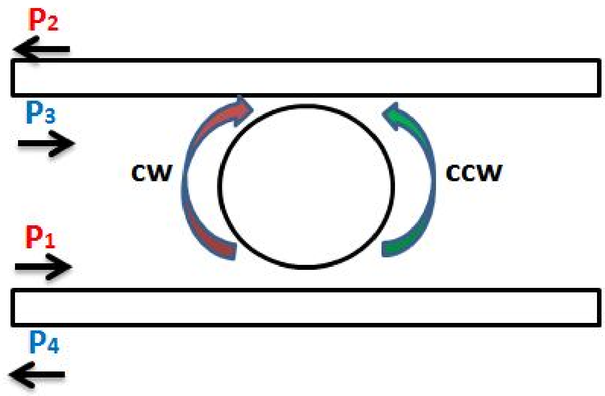

Fig. 1 Schematic diagram for predicting the non-reciprocal response

The light is coupled into the straight waveguide through the input port and evanescently couples into the microdisk as a counter-clockwise mode. In a microdisk, the mode is confined to the edge and propagates like a whispering-gallery mode. In such a scenario, two directions of propagation are possible viz. the clockwise (CW) and the counter-clockwise (CCW). Non-linear gain suppression in active materials can cause only one of these modes to be the dominant mode and the microdisk can operate in a unidirectional manner [5]. The unidirectional behavior is explained by using the rate law equations.

$$G_{CW} = \frac{\Gamma g v_g (N - N_0)}{1 + \varepsilon_S |E_{CW}|^2 + \varepsilon_C |E_{CCW}|^2} = \Gamma g v_g (N - N_0)\left[1 - \varepsilon_S |E_{CW}|^2 - \varepsilon_C |E_{CCW}|^2\right]$$

$$G_{CCW} = \frac{\Gamma g v_g (N - N_0)}{1 + \varepsilon_S |E_{CCW}|^2 + \varepsilon_C |E_{CW}|^2} = \Gamma g v_g (N - N_0)\left[1 - \varepsilon_S |E_{CCW}|^2 - \varepsilon_C |E_{CW}|^2\right]$$

The optical gain for a mode in a resonator in the presence of gain suppression is expressed by the above equations. The term ε_S arises due to self-gain suppression and the term ε_C corresponds to the cross-gain suppression. Gain suppression effects in semiconductors are caused due to transient carrier heating and spectral hole burning. The exact explanation of the values of these variables are derived out of calculations and $\varepsilon_C = 2\varepsilon_S$ [5].

Due to the presence of the grating couplers, bragg-reflectors, MMIs, scatterers, surface roughness etc., small amount of signal gets reflected. The field reflection coefficient is very small and the reflected light can couple back into the microdisk like a CW mode (shown in figure 1 as P_3). However, there is less gain available for the CW mode due to cross-gain suppression as can be seen in the following equations. This propagating CW mode can couple out at the input port after traversing half the microdisk as P_4.

$$\frac{G_{CW}}{G_{CCW}} = \frac{\left[1 - \varepsilon_S |E_{CW}|^2 - \varepsilon_C |E_{CCW}|^2\right]}{\left[1 - \varepsilon_S |E_{CCW}|^2 - \varepsilon_C |E_{CW}|^2\right]} = \frac{\left[1 - \varepsilon_S |E_{CW}|^2 - 2\varepsilon_S |E_{CCW}|^2\right]}{\left[1 - \varepsilon_S |E_{CCW}|^2 - 2\varepsilon_S |E_{CW}|^2\right]} = 1 - \frac{\left[|E_{CCW}|^2 - |E_{CW}|^2\right]\varepsilon_S}{\left[1 - \varepsilon_S |E_{CCW}|^2 - 2\varepsilon_S |E_{CW}|^2\right]}$$

$$|E_{CW}|^2 \ll |E_{CCW}|^2 \Rightarrow G_{CW} < G_{CCW}$$

If the input power is P_1, the output at the drop port is P_2, after reflection from the drop port the power is P_3 and the output power from the CW mode that couples out at the input port is P_4 (see figure 1). The symmetry of the path suggests the same ratio of input and output powers i.e. reciprocal behavior. The mathematical simulation for this ratio product yields a non-reciprocal behaviour at small input powers (P_1), as can be seen in the figure 2. Thus,

$$\frac{P_1}{P_2} \neq \frac{P_3}{P_4} \Rightarrow \frac{P_1 P_4}{P_2 P_3} \neq 1$$

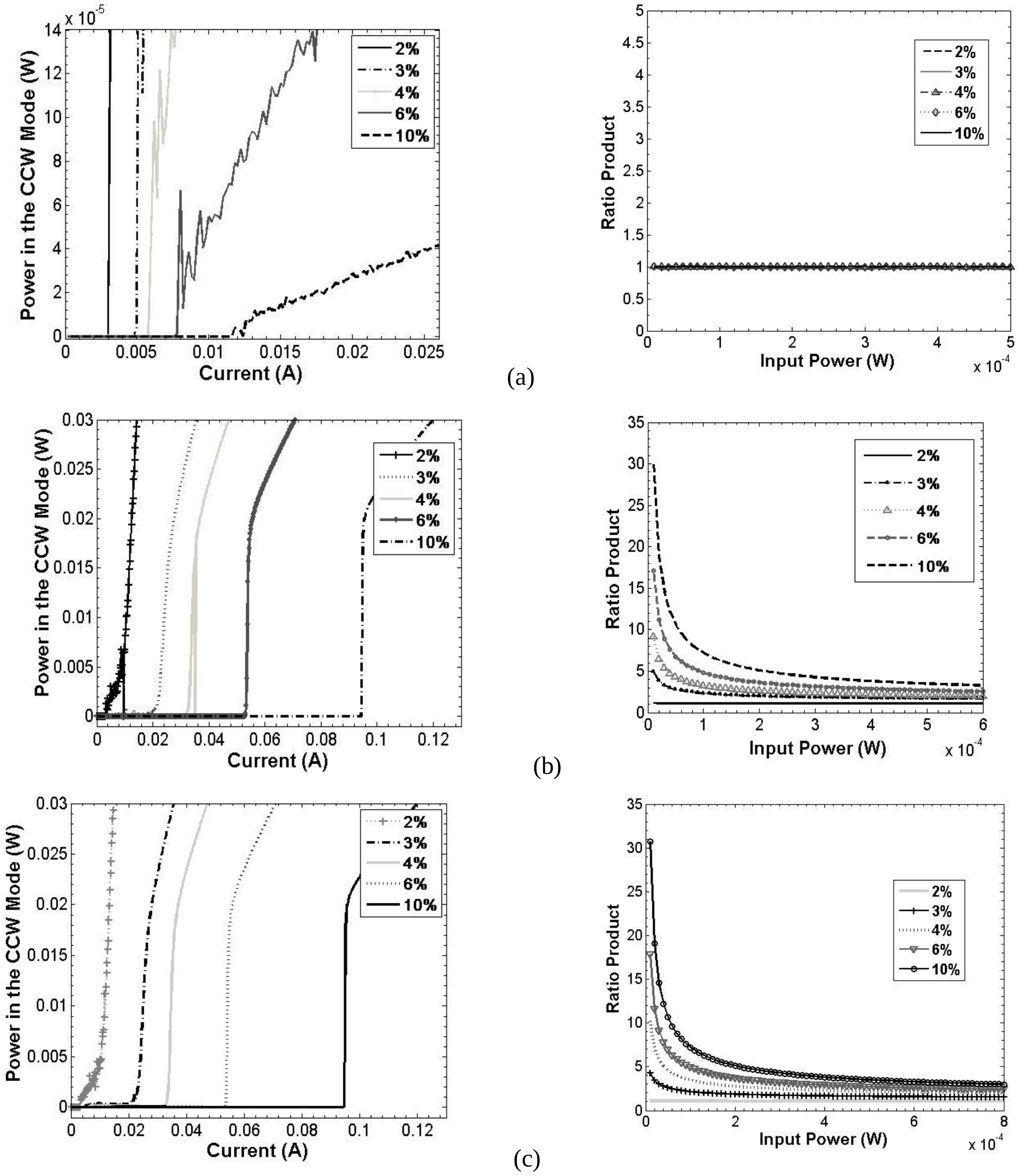

Fig 2. Lasing thresholds and ratio product calculations for varied coupling between the straight waveguide and microdisk : (a) when gain suppression and coupling between clockwise and counter-clockwise modes are absent (variation in field coupling between the waveguide and disk has no effect), (b) when gain suppression is taken into account, and (c) when gain suppression and coupling between the clockwise and counter-clockwise modes are taken into account

The result can be seen for varied power coupling between the straight waveguides and the microdisk. Current injection was varied to obtain the corresponding lasing threshold for varied coupling and the simulations were carried out again by keeping the current injection just below the lasing threshold for corresponding coupling between the disk and the straight waveguide. The lasing thresholds for the CCW mode can be seen in the figure 2. In the absence of gain suppression, the ratio product is 1 due to the symmetry of the device. When gain suppression is included, the device exhibits a non-linear and non-reciprocal response with changing input power levels, as shown in figure 2(b). The non-reciprocal response is valid for low power level (tens of microwatts) of the input light as can be obtained in heterogeneously integrated microdisks. Isolation number higher than 30 is seen in simulations. At higher power levels, like used in telecommunication, though the device still exhibits a non-linear response, there is no unidirectional propagation.

The effect of coupling between the clockwise and counter-clockwise modes is little, however when the coupling between the modes increases, the non-reciprocal response is only achieved for higher field coupling between the straight waveguide and microdisk. At higher coupling between the modes, a bi-stable behaviour is observed as more power gets coupled into the CW mode due to power of the CCW mode or vice-versa, and thus the cross gain suppression is reduced. The values for the conservative and dissipative coupling coefficients between the CW and CCW modes have been taken from the supplementary information in the reference [6].

Conclusion

An on-chip non-reciprocal device is an extremely important component for communications and sensing. The cross gain suppression between the modes in a III-V microdisk evanescently coupled with straight waveguides, induces the unidirectional behaviour in the device. Isolation numbers of greater than 30 have been predicted in the simulations. The device however is very wavelength specific as it would only operate at the resonance wavelengths of the microdisk. The non-reciprocal behaviour is observed at low power levels and not at high power levels as used in telecommunication.

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