Non-reciprocal transmission in ring resonators with saturable absorption

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Abstract

On-chip non-reciprocal devices are useful building blocks for all-optical signal processing but are hard to integrate on-chip. Magneto-optic or nonlinear devices can be used but these require strong magnetic fields and high optical powers respectively.

We use a non-linear add-drop ring resonator to enable nonreciprocal behavior at reasonable powers (~10 dBm). The ring has different power coupling coefficients $\kappa_1 > \kappa_2$ to the bottom and top bus waveguides which results in different powers in the ring when going from the add to the drop port and vice versa.

By adding a saturable absorber in the ring we turn this difference in power into a difference in transmission since in one direction the loss will be saturated while the other direction will have significant extra loss, breaking the reciprocity in the system. In this work we simulate the theoretical properties and discuss the experimental feasibility of an on-chip implementation of this device. With a simple saturable absorber model we simulate 34 dB extinction ratio between the different propagation directions with only 2.3 dB of insertion loss in the forward direction.

Introduction

All optical signal processing could accelerate real-time tasks with optical inputs such as in-line denoising and machine learning by staying in the optical domain and avoiding slow analog-to-digital converters. Nonreciprocal devices are a basic building block to realize these optical systems but they remain hard to integrate. These devices require either strong magnetic fields combined with exotic magneto-optic materials or high optical power to use optical nonlinearities efficiently [1] [2] . This last requirement can be relaxed by using a resonator to build up power. We use an add-drop ring resonator augmented with a saturable absorber (SA) to enable low power nonreciprocal behavior.

Design

Importantly our ring has different power coupling coefficients $\kappa_1 > \kappa_2$ to the bottom and top waveguides. This results in different powers in the ring when going from the add to the drop port (Fig. 1a) and vice versa (Fig. 1b). We first analyze the ring without the SA and using the formulas described in [3] we find:

$$\frac{P_{ring}^{(a)}}{P_{ring}^{(b)}} = \frac{\kappa_1}{\kappa_2}$$

Since the SA is not included in this calculation, it is a linear system and the power in the ring scales linearly with the power inserted from the bus waveguide.

This inserted power only depends on the coupling gap and the input power. Assuming equal input power it is the asymmetry in coupling gaps which results in an asymmetry of power in the ring. By adding a saturable absorber this difference in power in the ring results in a difference in transmission when going forward from the add to the drop port or backward (Fig 1c).

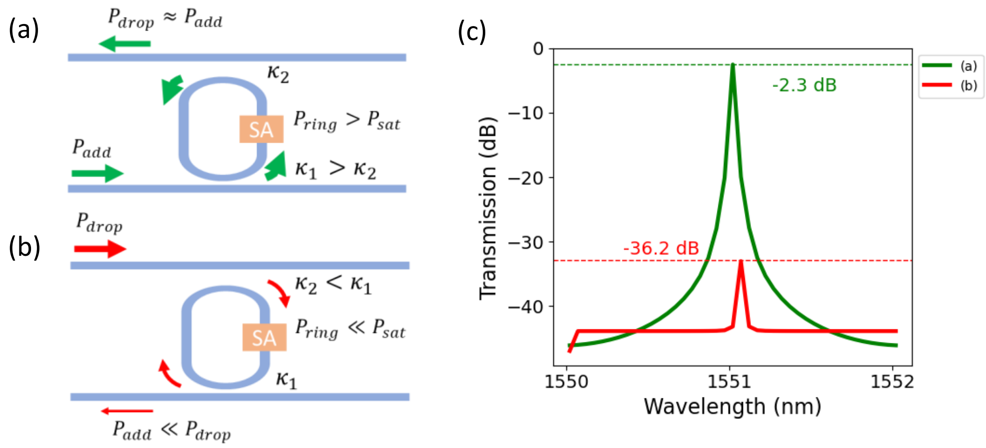

Fig.1 ***(a)*** *Schematic optical transmission from the add to the drop port, the power coupling to the ring* $\kappa_1 = 0.03$ *is strong enough to partly saturate the saturable absorber (SA), have a buildup of power in the ring and transmit power to the drop port,* ***(b)*** *In the other direction, the coupling to the ring* $\kappa_2 = 0.01$ *is weaker which results in considerable absorption in the SA, little power buildup in the ring and a low transmission from the drop to the add port* ***(c)*** *Simulated power transmission for (a) and (b)*

Nonreciprocal response

For simulating the device shown in Fig.1 we assume a simple equation for the saturable absorber loss :

$$\alpha_{SA} = \frac{\alpha_0}{1 + \frac{P_{ring}}{P_{sat}}}$$

We assume the following values for the SA :

$$P_{sat} = -2\ dBm\ , \kappa_1 = 0.03, \kappa_2 = 0.01\ , \alpha_0 = 10\ dB$$

The saturation power is quite realistic but the high extinction of 10 dB will be challenging to achieve in a practical system.

Because the loss in the ring is directly determined by the power in the ring it is important to take into account the dynamics of the buildup of power in the ring as there is no guarantee that the power will reach the steady state described above.

We use Lumerical Interconnect time domain simulation in parallel with an iterative matrix method in Python to simulate the system. The matrix method works by determining the loss in the ring at every time step by the power in the ring at that moment. This technique takes into account the transient buildup.

For nonreciprocal device we want to optimize both the rejection of the backward propagation and the forward insertion loss. Fig. 2(a) shows their values for different coupling coefficients. We choose k1=0.03 , k2=0.01 as optimum because there is a good tradeoff between only 2.4 dB insertion loss in the forward direction but 41 dB loss in the backward direction.

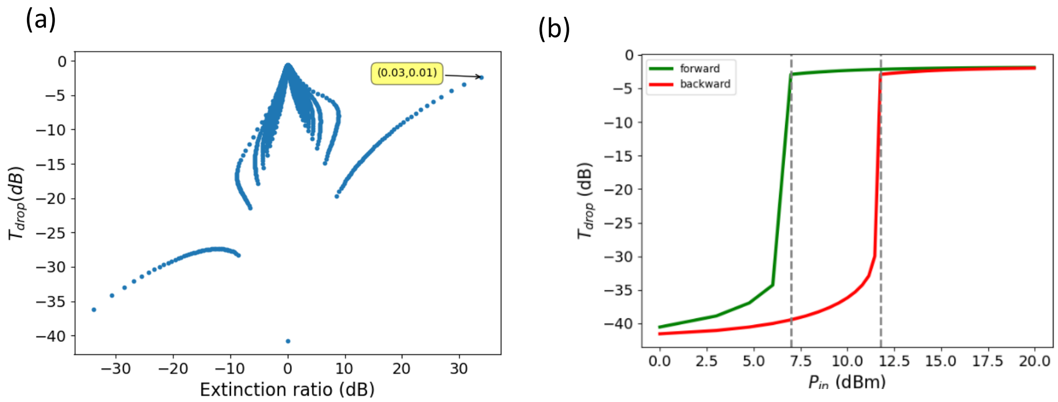

Fig.2 (a) Plotting the two figure of merits for nonreciprocal devices against each other, each point is a different combination of coupling coefficients κ_1, κ_2
(b) Forward and backward transmission to drop port in function of the input power, the nonreciprocal range is from 7 to 12 dBm

Both Lumerical and the matrix method show that the system does not always end up in one of the steady-state solutions without SA described above. Fig. 2b shows that if the input power is low the losses in the SA will be too high preventing power buildup even in the forward direction. The non-reciprocal response persists from 7 to 12 dBm input power, making sure that the system is robust to power fluctuations.

However the nonreciprocal behavior disappears if there are simultaneous beams going forwards and backwards. This is a problem for using it as an optical isolator but can be of use in all-optical signal processing.

Dynamic behavior

Aside from the nonreciprocal response, this system also displays some interesting nonlinear dynamic properties. By giving our models initial conditions where at t=0 there is high power in the ring the system evolves to a high transmission state even for the backwards propagation (see Figure 3) . This is because the initial high power bleached the SA making the power buildup possible and once the power is built up the lossesremain low. It is the reservoir of photons built up in the beginning which keep partly saturating the SA.

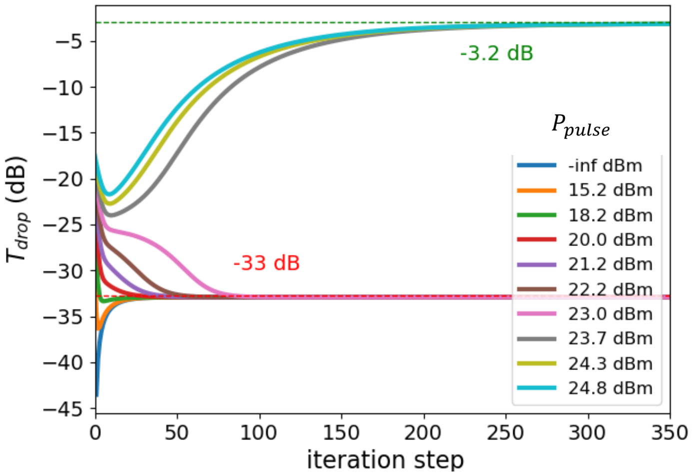

Fig.3 A strong pulse can saturate the absorption allowing for transient power buildup resulting in low loss transmission even in the backwards directions

This theoretical concept of an initial high power can be experimentally achieved by sending in a pulse of light after which the CW light will now have a low loss path to the drop port even after the pulse has passed. This behavior can be useful as an all optical memory [4] or as a spiking neuron in machine learning networks. The pulse threshold could be set by tuning the coupling gaps and the system could be reset by turning of the CW light or tuning the SA bandgap.

Conclusion

We show nonreciprocal behavior in a simple asymmetric add-drop ring by adding a saturable absorber. Although this system cannot isolate simultaneous beams it's dynamic properties could be used in all-optical signal processing applications such as denoising and machine learning.

Future work will focus on including realistic values for the extinction ratio and residual loss of the saturable absorber in simulation. These results can then be used to fabricate a real device by transfer printing a saturable absorber on a ring resonator.

References

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