All-Optical XOR Gate Based on a Saturable Cavity

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Abstract. We investigate the theoretical properties of a novel all-optical XOR gate design consisting of a saturable absorber in an all pass ring resonator. The two resonant inputs are combined in a 3 dB splitter which is then connected to the ring, where the pass port provides the XOR output. Using analytical methods we optimize the coupling constant of the ring and determine the power range over which the XOR operation is retained.

1 Introduction

All-optical signal processing could accelerate real-time tasks with optical inputs, such as inline denoising and photonic machine learning, by staying in the optical domain and avoiding slow analog-to-digital converters. All-optical gates are basic building blocks to realize these systems but these gates often require complex devices[1,2]. One of the basic logic gates is the XOR gate which provides a logical 1 as output only if one but not both of the inputs are 1. There have been all-optical demonstrations of an XOR gate but they are usually based on active elements [3]. We analyze an all-pass ring resonator augmented with a saturable absorber (SA) and show that by combining two inputs in a 3 dB splitter and coupling the output to the ring with SA , it can act as a passive all-optical XOR gate.

2 Methods and Results

For an all-pass ring resonator with an input field at the resonance frequency, we can express the field in the ring at steady state as [4]:

$$E_r = a_0 t_1 E_r + k_1 E_{in} \Rightarrow E_r = \frac{k_1}{1 - a_0 t_1} E_{in} \tag{1}$$

With E_r the field amplitude in the ring, a_0 the round trip loss, t the field transmission at the ring coupler, $k = \sqrt{1 - t^2}$ the field coupling constant and E_{in} the input field amplitude. From this we can get the field at the pass port E_p as:

$$E_p = tE_{in} - kE_r \Rightarrow E_p = \frac{t - a_0}{1 - a_0 t} E_{in} \tag{2}$$

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The relative power transmission to the drop port, $T_{pass} = (\frac{E_p}{E_in})^2$, only depends on the single round trip field transmission of the ring, a_0, and the field transmission coefficient t. By choosing the coupling gap so $t = a_0$ we get critical coupling, meaning $T_{pass} = 0$. In our design however, we add a saturable absorber (SA) in the cavity, resulting in a power-dependent loss in the ring:

$$\alpha_{SA} = \frac{\alpha_0}{1 + \frac{P_{ring}}{P_{sat}}} \tag{3}$$

$$a = a_0 e^{-\alpha_{SA}} \tag{4}$$

with α_{SA} the loss coefficient of the SA dependent on the power in the ring P_{ring}, the saturation power P_{sat} and the loss constant of the SA α_0. a is the power dependent round trip transmission coefficient taking into account the losses in the SA and the round trip loss of the ring itself a_0.
The steady state equations in the ring now becomes:

$$E_r = E_r a_0 e^{-\frac{\alpha_0}{1+\frac{P_{ring}}{P_{sat}}}} t + kE_{in} \tag{5}$$

By normalizing all powers and fields w.r.t. the saturation power $A^2 = \frac{P}{P_{sat}} = \frac{E^2}{E^2_{sat}}$ we can simplify this to:

$$A_r = A_r a_0 e^{-\frac{\alpha_0}{1+A_r^2}} t + kA_{in} \tag{6}$$

This is a transcendental equation and can not be solved analytically. Solving for A_{in} however results in a simple analytical equation:

$$A_{in} = \frac{A_{ring}}{k}(1 - a_0 e^{-\frac{\alpha_0}{1+(A_{ring})^2}} t) \tag{7}$$

Which we can use to investigate the behaviour of this system.

The mechanism to use this system as a logic gate is that the ring loss depends on the input power which in turn means that for a fixed coupling constant critical coupling will only be achieved at a specific power where: $t = a = a_0 e^{-\frac{\alpha_0}{1+A_r^2}}$. For our purposes we wan the limit of high ring powers to have critical coupling. Looking at the limit at infinity $\lim_{A_r \to \infty} a = a_0 e^{-\frac{\alpha_0}{1+A_r^2}}$ this reduces again to $t = a_0$ as the SA losses are completely saturated. As these high ring powers correspond to high input powers, this means at high input power the transmission will tend to $T_{pass} = 0$.

Using the parameters listed in Table 1 , where $t = a_0$, we show that the system has 3 regimes as shown in Fig. 1:

- for low input powers the SA has high losses, all light coupled in the ring gets absorbed so almost all the power is transmitted to the pass port. The transmission is high but the absolute output power will be low.
- for high input powers the SA is saturated, the light will resonate in the ring and the light will interfere destructively with the input light resulting in a low transmission to the pass port with a horizontal asymptote at $P_{pass} = 0$.

– for intermediate powers the SA gets somewhat saturated and the power starts building up in the ring so the pass transmission goes down, but since the absolute input power is going up a maximum will be reached at some power P_{in}^{max}.

Table 1. Parameter values

a_0	t	saturable loss [dB]/α_0
0.98	0.98	2.5/0.29

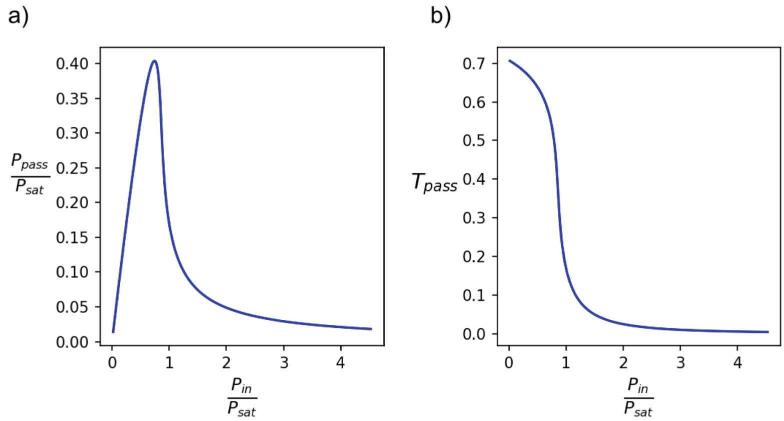

Fig. 1. Power response of the all pass ring with a saturable absorber (parameters from Table 1). (a) Pass power and (b) Pass transmission.

As an input to the saturable ring we will now consider an in-phase combination of 2 input bitstreams by using e.g. a 2×1 MMI:

$$E_{in} = \frac{E_1}{\sqrt{2}} + \frac{E_2}{\sqrt{2}} \tag{8}$$

$$\frac{P_{in}}{P_{sat}} = \frac{(A_1 + A_2)^2}{2} \tag{9}$$

Figure 2 shows the output the ring with SA as a function of the two input powers. By selecting the power corresponding to a 1-bit, equal to twice the input power with the maximum output $P_{on} = 2P_{in}^{max}$ this circuit can be used as an XOR gate. If both inputs are "off" there is no power at the output, if only one input is "on" the input to the saturable ring will be P_{in}^{max} and the output will be maximal since the 3-dB splitter will halve the power if only one port is "on" and if both the inputs are "on" the maximum is overshot , the ring input will be $4P_{in}^{max}$ and the transmission will be low. Figure 2 also shows that small deviations from $P_{on} = 2P_{in}^{max}$ will already result in a bit flip for the 01 input.

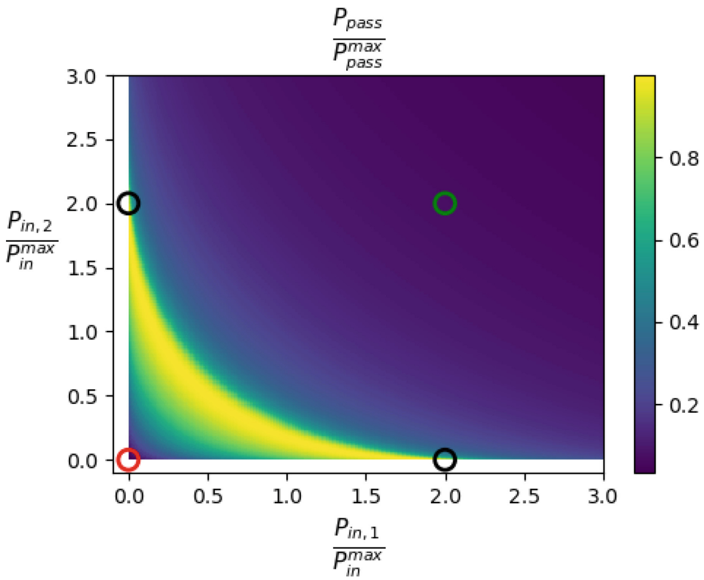

Fig. 2. output of the saturable ring dependent on the 2 input powers, the circles show the input states when $P_{on} = 2P_{in}^{max}$, black represents the 01 or 10 state with high output, green the 11 state and red the 00 state which both have low output power. This is exactly the expected response for the XOR operation.

To study this sensitivity and investigate if there are more optimal values for P_{on} we plot the output for each logical input state as a function of P_{on} corresponding to the logical one in Fig. 3. We also study errors on the logical zero by looking at different values for $P_{off} \neq 0$ proportional to the on-power $P_{off} = aP_{on}$. For the 00 state we see that for $P_{off} = \frac{P_{in}}{10}$ we get a high output power while the logical output should be 0. $P_{off} \leq \frac{P_{in}}{100}$ results in low outputs for the 00 input state and an output power > 80% of the maximum for the 10 and 01 inputs, if also $1.3P_{in}^{max} < P_{on} < 1.9P_{in}^{max}$. Lastly the 11 state results in a low output as long as $P_{on} > P_{in}^{max}$. The union of these result in an operating range of $1.3P_{in}^{max} < P_{on} < 1.9P_{in}^{max}$ and $P_{off} \leq \frac{P_{in}}{100}$. This is quite a narrow range, future analysis will focus on extending this range. However the narrow range might prove useful in pulsed neuron applications. Figure 2 also shows that different values for P_{on} can result in different gates e.g. the AND gate with $P_{on} = \frac{P_{in}^{max}}{2}$. Additionally, tuning the phase between the 2 inputs will result again in different gates and this will be investigated in future work.

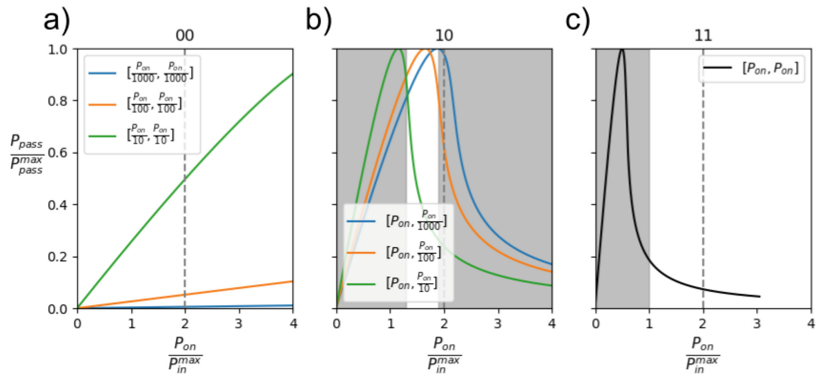

Fig. 3. Output of the XOR system for input powers deviating from the ideal powers, for a logical input of a) 00 b) 10 c) 11

3 Conclusion

We show that an SA ring resonator combined with a 3 dB splitter can be used as an all-optical XOR gate. The XOR behaviour is however very sensitive to power deviations making for an impractical device. Future work will focus on increasing the operation range and investigating if the XOR behaviour is retained for more realistic values of the SA insertion loss. However for use in pulsed neuron systems the narrow power range might be desirable[5]. To this end we will continue developing the analytic framework to characterize the gate properties as well as employ numerical techniques. Eventually a possible implementation of this system could be fabricated using quantum dots as a passive saturable absorber because they require no external power source and have comparably low saturation powers.

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