Nonvolatile switching in a ring resonator with saturable absorption

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***Abstract*—We investigate the theoretical properties of a novel all-optical switch design consisting of a saturable absorber in an add-drop ring resonator. Using a modified transfer matrix method we demonstrate nonvolatile switching, where the routing persists even after the control signal is deactivated.**

***Index Terms*—all-optical switching, ring resonator, all-optical memory, saturable absorber, latching**

I. 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 switches are a basic building block to realize these systems but usually require high input powers and complex devices [1]. We simulate a simple add-drop ring resonator augmented with a saturable absorber (SA) and show low power all-optical switching. Moreover we show nonvolatile behaviour where the routing persists even after the control signal is removed. This allows for low-power operation and provides memory capacity for all-optical signal processing such as photonic reservoir computing [2].

II. Methods and results

In a simple add-drop ring resonator the transmission to the drop port is given by [3]:

$$T_{drop} = \frac{P_{drop}}{P_{in}} = \frac{\kappa_1^2\kappa_2^2 a}{1-2\tau_1\tau_2 a_0 + \tau_1^2\tau_2^2 a_0^2} \tag{1}$$

The relative power transmission to the drop port, T_{drop}, only depends on the fixed single round trip field transmission of the ring, a_0, and the field coupling coefficients κ_1 and κ_2 as the field transmission coefficients are related to the coupling coefficients by $\tau_1 = \sqrt{1-\kappa_1^2}$ and $\tau_2 = \sqrt{1-\kappa_2^2}$. The coupling coefficients, determined by the coupling gaps, can be used to ensure high transmission to the drop port. In our design however, we add a saturable absorber (SA) in the cavity (see Fig. 1), resulting in a power-dependent loss in the ring:

$$\alpha_{SA} = \frac{\alpha_0}{1+\frac{P_{ring}}{P_{sat}}} \tag{2}$$

$$a = a_0 e^{-\alpha_{SA}} \tag{3}$$

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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 now the updated 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.

Since the power in the ring determines the loss and the loss determines the power in the ring, this system cannot be analyzed with simple steady state techniques anymore and methods taking dynamics into account are necessary e.g steady state solutions with high transmission to the drop port are not necessarily reached as the loss in the SA is higher during the power buildup than in this steady state.

To investigate the properties of this system we use an iterative transfer matrix method and validate it with Lumerical Interconnect time domain simulations. The matrix method works by determining the power in the ring at every time step and updating the SA transfer matrix with the corresponding loss. Using the parameters listed in Table I we show that the system has 3 regimes (see Fig.1(c)):

- for low input powers ($<$ 2.8 mW) the SA has high losses, all light coupled in the ring gets absorbed so almost all the power is transmitted to the pass port.
- for high input powers ($>$ 13.8 mW) the SA is saturated, the light will resonate in the ring and the transmission to the drop port is high
- for intermediate powers the system is bi-stable: the presence or absence of an inital pulse (Fig. 1) before the power is lowered to its steady state value, can make the ring transmit almost everything to the drop port or the pass port respectively.

TABLE I
Parameter values

P_{in}	P_{sat}	κ_1	κ_2	a_0	α_0
8 mW	0.6 mW	0.01	0.012	0.998	1.15

For these intermediate powers the transmission to the drop port will be near zero if the initial pulse power is low (Fig.1(b)) but if the initial pulse power is high ($>$ 13.8 mW) and allowed enough time to saturate the SA the system evolves to a high transmission state (Fig.1(a)) . The initial high power bleaches

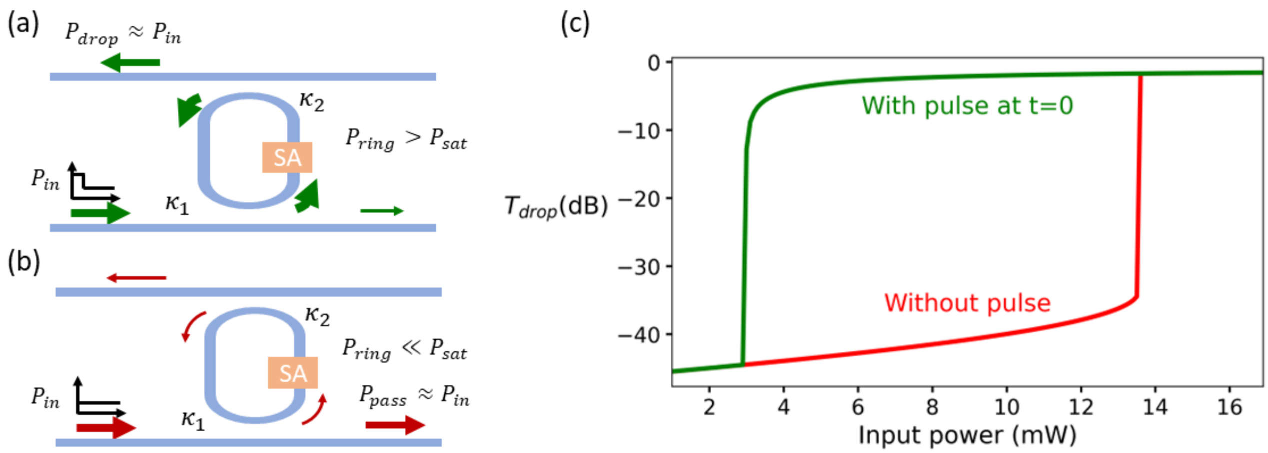

Fig. 1. (a) Schematic optical transmission from the input to the drop port of a continuous wave input with an initial pulse (b) without an intial pulse (c) Simulated power transmission to the drop port for (a) (green) and (b) (red) for a saturation power of 0.6 mW and optimized coupling coefficient and input power listed in Table I

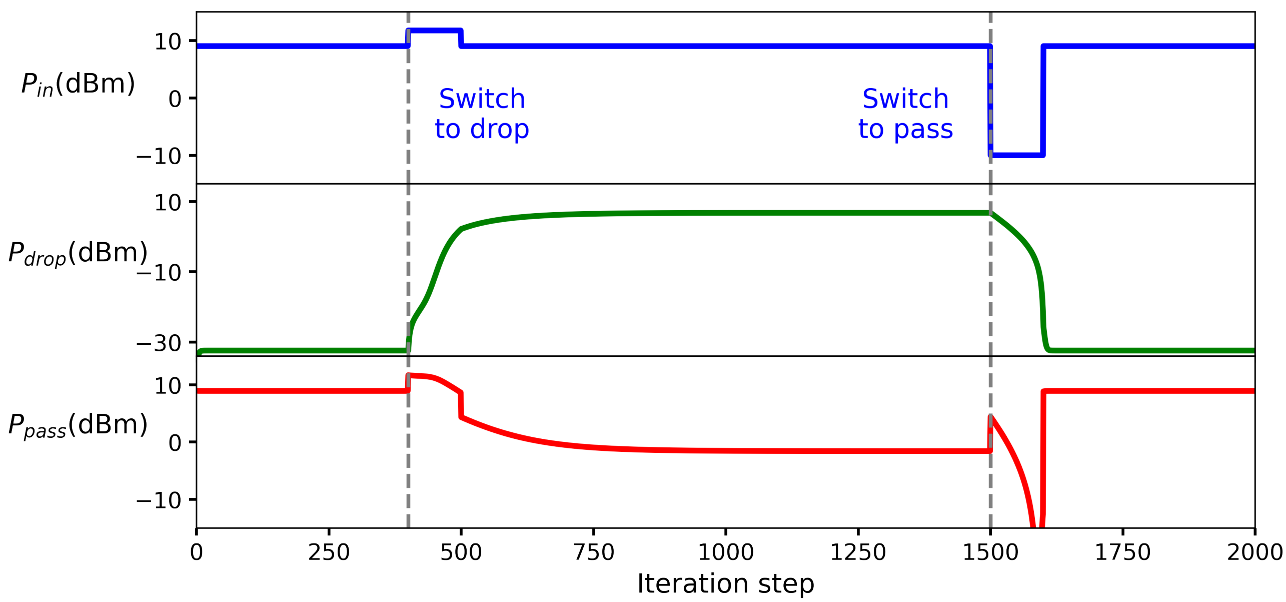

Fig. 2. (a) Dynamics of the saturable absorber based all-optical switch (parameters in Table I) using the modified transfer matrix method: first the input light is routed to the pass port, when applying a pulse at step 300 it is routed to the drop port and by removing the CW for a period at step 1500 it is routed back to the pass port. For the two states the extinction ratios are 30 dB and 10.1 dB and the insertion losses are 0.1 dB and 1.8 dB respectively

the SA which makes the power buildup possible even at the lowered intermediate power and the large reservoir of photons in the ring will keep saturating the SA while being replenished by the incoming input power. This will ensure the continuous wave (CW) light of intermediate power ($2.8mW < P_{in} < 13.8mW$)will have a low loss path to the drop port even after the power has been lowered back. It is in this bistable regime that the ring can be used as a nonvolatile all-optical switch.
This behavior could be useful as an all-optical memory, for all-optical switching and as a spiking neuron in neural networks. The switching can either be controlled by applying different powers at the input or with a separate control signal since the SA loss only depends on total power $P_{in} + P_{control}$. The control could be a different wavelength or come from different ports of the ring to not interfere with the input light and the pulse threshold can be set by tuning the coupling gaps.
In Fig.2 we show how 8 mW CW light can be switched to the drop port by applying a pulse of 6 mW on top. This routing is retained after the total power has returned to 8 mW. Only by turning off the light for a long enough period do we route the light back to the pass port. These simulations are done with the values in Table I.

III. Conclusion

We show bi-stable nonvolatile switching of an SA ring resonator, where the routing persists even after the control signal is removed. This nonvolatile behaviour enables a memory function which can be useful in all-optical signal processing applications such as denoising and spiking neural networks. Future work will focus on developing an analytic framework to characterize the switching properties such as the power range and the switching speed and using this to optimize the system for realistic saturable absorber characteristics. A possible implementation of this system would be to use quantum dots as a passive saturable absorber because they require no external power source and have comparable saturation powers as the ones considered in this work.

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