Optical Modulation in a Si Microring Resonator Inspired by Biological Classical Conditioning

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Abstract: We propose and numerically demonstrate photonic classical conditioning in a Si microring resonator, to emulate Pavlov's dog experiment using the insulator-metal transition in a VO_2 thin film patch integrated with the resonator.

1. Strategy of optically emulating Pavlov's experiment

In the biology regime, classical conditioning is a learning procedure where a stimulus produces different responses before and after the procedure. It is a form of associative learning closely related to associative memory, a biological concept that is being explored actively for non-von Neumann computing [1]. In this work, we demonstrate via numerical simulation that, the biological classical conditioning can be emulated using a vanadium dioxide-integrated Si microring resonator. The "biological learning" is emulated by exploiting the metal-insulator transition in the vanadium dioxide (VO_2).

The best-known biological classical conditioning experiment is Pavlov's dog experiment, which involves a bell, food and a dog. Before the learning procedure, ringing the bell (a neutral stimulus) does not induce the dog to salivate (i.e. no response). The learning, or the conditioning, involves pairing the bell ringing with the presence of food, which is an unconditioned stimulus. After the learning, ringing the bell alone can induce dog salivation (i.e. a conditioned response), and the previously neutral stimulus becomes a conditioned stimulus.

In this work, the classical conditioning is emulated using a Si microring resonator evanescently coupled with two straight bus waveguides (Fig. 1). The bell, food and salivation in Pavlov's experiment correspond to three ports of the waveguides, which are labeled as B (for bell), F (for food) and S (for salivation). The Si microring resonator is integrated with a VO_2 thin film patch. The VO_2 patch can transit between the metallic and the insulating state, which modulates the optical transmission from port B to port S (i.e. transmission S/B), as well as that from port F to port S (i.e. transmission S/F). The biological learning procedure can be mapped onto this microring resonator following the steps listed in Table 1. Here, a threshold transmission T_{th} is used to distinguish digit 1 (for a finite response, including both conditioned and unconditioned responses) and digit 0 (for no response).

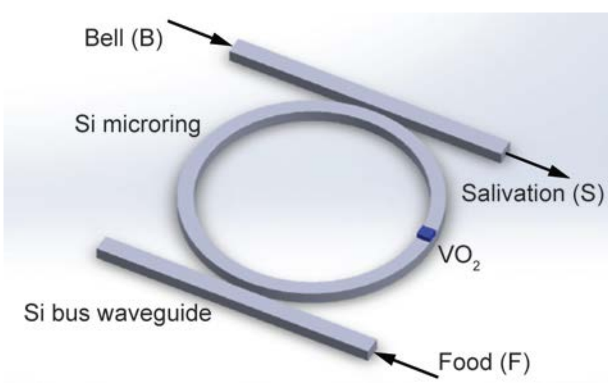

Figure 1. A dual waveguide-coupled Si microring resonator inspired by Pavlov's classical conditioning. The B input, F input and S output emulate bell, food and salivation, respectively.

Table 1. Optical implementation of the learning procedure using the Si microring resonator.

Learning procedure	Output requirement	VO_2 state
Before conditioning	$S/F > T_{th}$	Insulating or Metallic
Before conditioning	$S/B < T_{th}$	Insulating
During conditioning	$S/F + S/B > T_{th}$	Metallic
After conditioning	$S/B > T_{th}$	Metallic

As seen in Table 1, the output changes from $S/B < T_{th}$ to $S/B > T_{th}$ after the learning procedure, and it can be achieved by using the thermally driven phase transition in the VO_2 patch on top of the Si microring. The conditioning step is for the inputs B and F to induce sufficient heat inside the VO_2 patch to change it to the metallic phase, a phase transition that is not allowed for input B alone. This phase transition opens the S/B channel, and creates the contrast in the S/B transition observed before and after the conditioning.

2. Numerically simulated transmission modulation

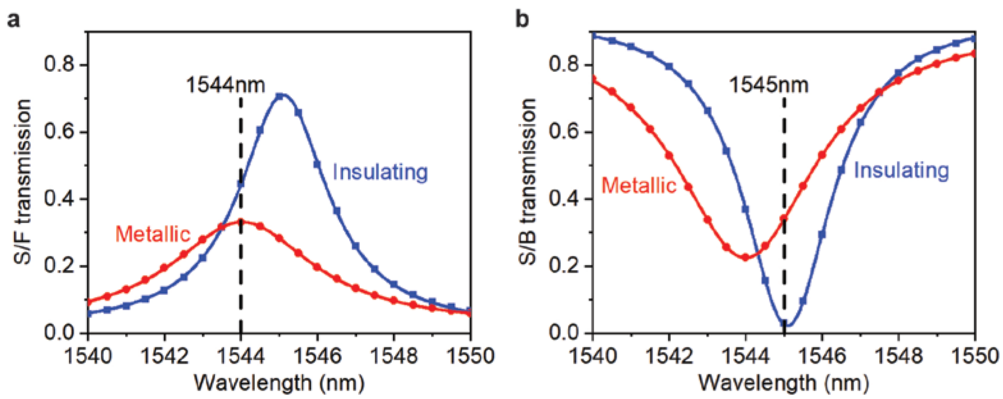

Figure 2. Numerically simulated transmission (a) from input port F to output port S, and (b) from input port B to S. The VO_2 is in either the insulating or the metallic phase. The working wavelength is 1544 nm and 1545 nm for the S/F and the S/B channel, respectively. The two channels work at slightly different wavelengths to eliminate the influence of coherent interference on light absorption in the VO_2 patch.

The emulation strategy is numerically verified using a finite-element solver (Comsol Multiphysics), with some representative results shown in Fig. 2. The device is based on a SOI (silicon-on-insulator) platform. All the waveguides, including both the microring and the straight bus waveguides, are single mode with a rectangular cross section of 220 nm × 500 nm. The microring has an inner radius of 4.75 μm, and the coupling gap is 50 nm. Figure 2 shows the output S for a single (either F or B) input. To simplify the analysis, we make the learning procedure of $S/F + S/B > T_{th}$ in Table 1 more restrictive as $S/F > T_{th}$. The transmission at the two working wavelengths in Fig. 2 shows that T_{th} can be set within 0.03 and 0.33, allowing for a relatively large noise margin of 0.3.

In conclusion, we have demonstrated a device emulating Pavlov's dog using a Si micro-ring resonator with a VO_2 patch. The operation of the device relies on the thermally driven phase transition in the VO_2 patch, which has a strong temporal dependence [2]. This temporal sensitivity suggests that the device could be used in spiking neurosynaptic networks [3], where the temporal differences between input optical pulses encode information.

3. References

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