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Spotlight on "Experimental observations of thermo-optical bistability and self-pulsation in silicon microring resonators"

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Spotlight summary:

Even though the origins of optical resonators date back to the pioneering work by C. Fabry and A. Pérot over a century ago, research on optical resonators is still surprisingly vivid. Optical resonators are a kind of magic box from which unexpected phenomena keep on coming out, especially when different physical mechanisms simultaneously take place and mutually interact.

In particular, nonlinear dynamics in optical resonators is a never-ending source of discoveries. Let us consider, for instance, bistability and self-pulsation effects, which can be originated in a resonator at a sufficiently high optical power level. Bistability is related to the existence of two possible stable states, and is of particular interest, for example, in the realization of optical memories, flip-flops and logic units. Self-pulsation, typically occurring at higher power levels, is instead associated with a periodic swinging of the cavity between two non-stable states, which results in the breaking of an input continuous wave into a pulse-train-like output waveform. Here, applications in the field of on-chip clock distribution are envisioned. While nowadays it is not unusual to hear about bistability and self-pulsation, if we were to think we know everything about the nonlinear dynamics of optical resonators, we are probably in for some big surprises.

In fact the physics underneath nonlinear processes is much richer than one would expect at first, especially in semiconductor cavities such as silicon microring resonators. In silicon waveguides, free carriers generated by nonlinearity play a twofold and self-counteracting role in terms of refractive index change: a decrease in the refractive index due to free-carrier dispersion (FCD) and an increase in the refractive index due to the thermooptical (TO) effect, that is waveguide heating associated with interband and intraband carrier relaxation and phonon excitation. Depending on the time response of these two effects, the refractive index change can be balanced or not, resulting in a strongly different nonlinear dynamics of the resonator.

In a passive silicon microring, the free-carrier lifetime and the thermal decay time are both constants, so that the only way to trigger and control self-pulsation is through the power and the wavelength of the input field. Having a way to control at least one of these characteristic times would provide a powerful knob to arbitrarily switch the state of the resonator across different nonlinear regimes, giving an additional degree of freedom to control bistability to self-pulsation mechanisms.

The work by the group of S. Chen L. Zhang *et al.* proves that this is possible indeed. They investigated the nonlinear dynamics of a silicon microring resonator with an embedded PN junction. When no voltage is applied to the junction, free carriers (that in the 1550 nm wavelength range are mainly induced by two photon absorption) are naturally swept out of the waveguide by the built-in field of the PN junction and recombine at the Si-SiO$_2$ interface in a time scale of about 3 ns. In these conditions, FCD and TO effects are effectively balanced and self-pulsation is experimentally observed for an input power as low as a few milliwatts. By detuning the input wavelength with respect to the microring resonance, the frequency of self-pulsation can be continuously tuned from 10 to 20 MHz, and the duty ratio itself of the output waveform can be varied almost from 1 to 0. If the PN junction is reversed biased (-1 V), free carriers are swept out of the optical waveguide much more quickly, so that the free carrier lifetime reduces by two orders of magnitude (about 0.03 ns). In this regime, the balance between the free-carrier dispersion and thermooptical effect is broken and self-pulsation is inhibited at any input power and wavelength. This means that the nonlinear dynamics of a resonator can be dramatically modified in a fully controllable way simply by means of an external electric control.

These results open new horizons in the application of integrated optical resonators, which turn out to be extremely flexible devices, both in the linear and nonlinear regime, as well as key building blocks for the next generation of reconfigurable photonic integrated circuits. For those people interested in fundamentals science, this work teaches us that the way towards a full understanding of optical resonators is still long and, who knows, maybe the most exciting part of the story is yet to come.

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