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Modelling Analytically the Dynamic Response of Thermo-Optic Phase Shifters

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Thermo-optic phase shifters are widely adopted to achieve dynamical reconfiguration of integrated waveguide circuits [1], with applications encompassing diverse fields, ranging from free-space beam steering and shaping [2] to quantum information experiments [3].

The operation of these devices basically relies on thermo-optic refractive index variations, which are controlled by locally heating the substrate with resistors deposited on the chip surface. The universality of the thermo-optic effect and the intrinsic simplicity of the thermal action have enabled the implementation of these dynamic components in multiple waveguide architectures, which include silica-on-silicon [3], silicon nitride [4], silicon-on-insulator [2] and femtosecond laser written (FLW) circuits [5].

The design process of thermo-optic phase shifters is often based on numerical simulations of the heat diffusion, which can describe even complex microstructured elements at the cost of non negligible computation times. On the other hand, approximated analytical models can be beneficial for a deeper understanding of the involved physical dynamics; however, to the best of our knowledge these have been reported in only few works in the literature. In addition, analytical studies have been mostly limited to the steady state [6, 7], or to provide very general figures on the dynamic behaviour [8]. Furthermore, such models may not be suitable to describe FLW devices, where waveguides are inscribed in 3D within a thick glass substrate.

Here we develop an analytical model for the heat diffusion, working in the typical geometrical settings of integrated waveguide devices, that allows to describe the static operation and the detailed dynamic response of thermo-optic phase shifters, and that may be applied to different waveguide fabrication platforms. We test experimentally the model predictions on FLW, thermo-optically controlled, Mach-Zehnder interferometers inscribed in a glass substrate, with different geometries and different depth below the surface. The good agreement between the experimental data and the theoretical predictions testifies the potential of this model (Fig. 1), notwithstanding the approximations on which it is based.

We further analyze microstructured devices, where insulation trenches have been machined on one waveguide's sides, to increase the device efficiency. We discuss how this approximated analytical approach can be helpful in guiding the engineering process, also in the case of these more complex architectures.

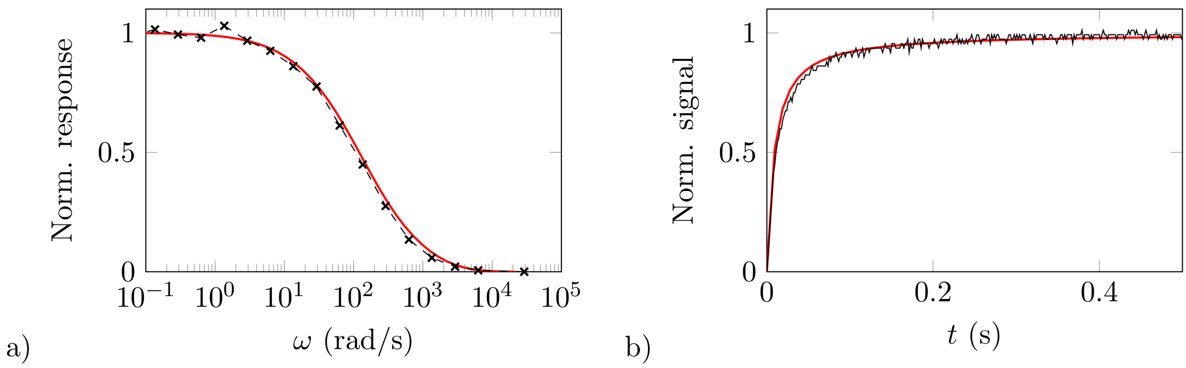

Fig. 1 Frequency response (a) and step response (b) of a FLW Mach-Zehnder interferometer, with a thermo-optic phase shifter realized on one arm [5]. The black crosses and the black thin line represent experimental measurements, operated on the optical output of the interferometer, in the regime of small modulations around the quadrature point (so that the optical signal can be considered linear with the phase shift). Red thick lines are the predictions from the analytical model.

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