Noninvasive monitoring and control in silicon photonics using CMOS integrated electronics: supplementary material

STEFANO GRILLANDA^{1,*a}, MARCO CARMINATI^{1,a}, FRANCESCO MORICHETTI¹, PIETRO CICCARELLA¹, ANDREA ANNONI¹, GIORGIO FERRARI¹, MICHAEL STRAIN², MARC SOREL³, MARCO SAMPIETRO¹, AND ANDREA MELLONI¹

¹Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, 20133 Milano, Italy

²Institute of Photonics, The University of Strathclyde, Glasgow G4 0NW, UK

³School of Engineering, University of Glasgow, Glasgow, G12 8QQ, UK

*Corresponding author: stefano.grillanda@polimi.it

^aS.G. and M.C. contributed equally to this work.

Compiled August 26, 2014

This document provides supplementary information to “Noninvasive monitoring and control in silicon photonics using CMOS integrated electronics,” (<http://dx.doi.org/10.1364/optica.1.000129>). It includes detailed information to support the description of the closed-loop model used in Section 5 “Locking the microring resonant wavelength” of the main manuscript. © 2014 Optical Society of America

OCIS codes: (130.0130) Integrated optics; (250.5300) Photonic integrated circuits; (230.5750) Resonators; (130.0250) Optoelectronics; (040.6040) Silicon.

<http://dx.doi.org/10.1364/optica.1.000129.s001>

1. DETAILED DESCRIPTION OF THE CLOSED-LOOP MODEL

A model of the control loop employed in Sec. 5 has been developed in order to choose the controller parameters and guarantee the stability of the feedback system.

Fig. S1(a) shows the schematic diagram of the control loop, where the main parameters of the building blocks of the system are indicated. Although the loop is generally described by a non-linear function, because of the typical anti-symmetric shape of the error signal ε (see Fig. 4) and of the quadratic response of the thermal actuator, for simplicity here we assume the case of small perturbations around the resonant wavelength λ_r , where a linearized model can be used. This assumption is strictly valid in the example of Fig. 5(a), where no significant shift from λ_r occurs; in contrast, in the example of Fig. 5(b), the instantaneous wavelength shift by 50 pm pushes the ring outside the linearity range of ε , which is limited to ± 20 pm around λ_r . However, the result of Fig. 5(b) demonstrates that the realized closed-loop system, that was designed according to the simplified linear model, is able to keep the ring locked also in this case.

The loop gain G_{loop} , whose magnitude is shown in Fig.

S1(b), can be described by the following equation

$$|G_{loop}| = \left| \frac{G_D}{1 + s\tau} \frac{k}{s} G_H \right|, \quad (\text{S1})$$

where $s = j2\pi f$, j is the imaginary unit and f is the electric frequency. In the following, the main contributions to the G_{loop} expression given in Eq. (S1) are discussed in order to point out the parameters that mainly affect the time response of the control system.

Starting from the CLIPP read-out block of Fig. S1(a), the current i_e collected by the CLIPP [see Fig. 2(a)] is demodulated by the integrated electronic chip in order to measure the optical intensity in the resonator and the error signal ε . In the experiment discussed in Sec. 5, the CLIPP is driven at a frequency $f_e = 1$ MHz and a lock-in bandwidth $B_e = 1$ kHz (two-pole) is used to extract the value of the conductance variation ΔG . A second filter with a bandwidth $B_d = 100$ Hz (single pole) is cascaded to extract the amplitude of the dithering signal applied to the heater ($f_d = 160$ Hz), thus resulting in time constant $\tau = 1/(2\pi B_d) = 1.59$ ms, which is ultimately the dominant time constant of the loop system.

The error signal read-out block contains a forward sensor

Fig. S1. (a) Block diagram providing a concept-level description of the closed-loop system utilized to achieve wavelength locking of the microring resonator. (b) Qualitative logarithmic plot of the magnitude of the loop gain $|G_{loop}|$ of the control system as a function of the electric frequency f .

transfer function $G_D = \Delta\lambda / \Delta\varepsilon$, that relates the wavelength detuning $\Delta\lambda$ experienced by λ_r to the corresponding variation of the error signal $\Delta\varepsilon$. As shown in Fig. 4(b), for $V_d = 100$ mV a wavelength detuning $\Delta\lambda = 20$ pm originates $\Delta\varepsilon = 300$ μ V, that is $G_D = 15$ μ V/pm. Regarding the *heater* block, since the time constant of the thermal actuator is typically in the μ s-time scale (that is negligible compared to τ), it can be simply described by a purely algebraic term G_H . According to the curve shown in the inset of Fig. 3(b), when a 2 V bias voltage is applied to the heater and $V_d = 100$ mV, the value of G_H is about 95 pm/V.

An *integral controller*, with transfer function $-k/s$, has been adopted in the loop system. The gain k is typically around 10^4 in order to guarantee stability of the loop system according to the Bode criterion. In this way, the closed-loop frequency results indeed around $f_c = 3$ Hz, well below the second pole at $1/2\pi\tau = 100$ Hz [Fig. S1(b)].

The controller is implemented in the digital domain by using a FPGA, in order to obtain more flexibility in setting the system parameter and more speed with respect to computer-assisted architectures. The trapezoid rule is used to approximate the integrator in the discrete domain, with a sampling rate of 899 Sa/s (i.e. fast sampling interval 1.1 ms).

The achieved response time of the closed loop can be significantly reduced by either acting on the control law or by enlarging the CLIPP detection bandwidth. For instance, with the actual CLIPP bandwidth settings, by simply moving to a proportional (with gain of about 6600) or proportional-integral controller, a 1 kHz closed-loop bandwidth could be easily achieved (response time of 160 μ s), yet at the price of larger voltage variations at the heater. On the other side, while maintaining an integral control law, the loop frequency can be shifted toward a higher frequency range by increasing the bandwidth, yet at the price of an increase in the noise (that grows with the square root of $1/\tau$, i.e. to achieve a $f_c = 1$ kHz, a noise increase of about one order of magnitude should be tolerated).