SOI and InP based on-chip 3x3 interferometers for wavelength interrogation

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We have successfully designed and characterized compact three-port interferometers on chip for accurate wavelength tracking. These interferometers are ideal candidates for on-chip read-out of photonic sensors such as ring resonators. On-chip implementation offers the advantage of low cost, high mechanical stability and accurate optical path length difference. We have realized devices in both Silicon-On-Insulator (SOI) and Indium Phosphide (InP) technology.

Keywords: On-chip interrogator, photonic sensor, ring resonator, 3x3 interferometer, ePIXfab, PARADIGM, multi-parameter sensing.

Introduction

Photonic multi-parameter sensing has attracted increased attention in recent years [1][2][3]. In particular, ring resonator (RR) based sensors are promising for gas sensing and bio sensing due to their high sensitivity to refractive index variations and their potential for multiplexing. In these applications, RRs are coated with a gas-selective coating or a layer of antibodies. The presence of the target gas or the bio-counterpart, respectively, causes a detectable shift of the resonance wavelengths. For bio sensing applications, the sensor is a single-use device which is read out by means of a stand-alone unit. For gas sensing, we propose to integrate the read-out unit with the sensor itself to obtain a small, robust, low-cost and accurate stand-alone system [1].

Sensor read-out concept

The concept is as shown in Figure 1. The wavelength of a narrow-band source is swept in time. The optical signal passes through an interferometer to enable time-to-wavelength calibration for each wavelength sweep. Using this calibration data, the transmission of the sensor vs. time is then translated to the wavelength response, from which the sensor read-out is obtained by means of a microprocessor. This concept enables the use of a low-cost laser, such as a Vertical Cavity Surface Emitting Laser (VCSEL), the wavelength of which is swept by sweeping the drive current [4]. The sweep-specific wavelength calibration provides a high-accuracy sensor read-out.

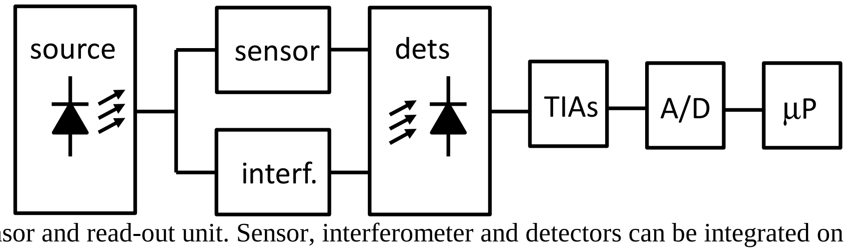

Figure 1. Sensor and read-out unit. Sensor, interferometer and detectors can be integrated on a single SOI chip, in InP technology also the source can be integrated.

3-Port interferometer

We propose to use a 3-port interferometer (Figure 2) which has three outputs at a 120° mutual phase difference, for the following reasons:

1. At any input wavelength, at least one output has considerable amplitude and derivative with respect to wavelength.
2. The combined outputs enable unambiguous tracking over wavelength spans larger than the Free Spectral Range (FSR). In comparison, a 2-port interferometer has two 180° out-of-phase outputs, and the sign of change is unknown at the boundaries of one FSR range, where the output derivatives to wavelength are zero.
3. It is insensitive to the modulation depth of the interference.

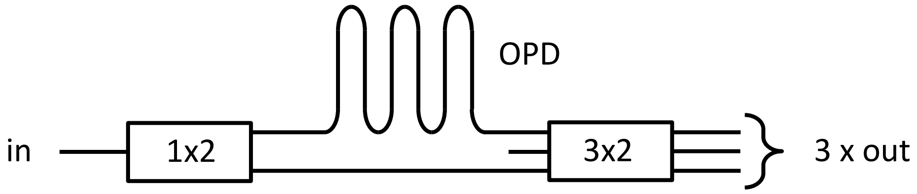

Figure 2. 3-port interferometer consisting of two splitters/combiners and an Optical Path length Difference (OPD). Note that one input of the 3x3 splitter/combiner is not used.

Interferometer in Silicon On Insulator

We realized the test circuit shown in Figure 3. It was fabricated at IMEC using the multi-project wafer run service of the Silicon Photonics platform ePIXfab [5]. The laser input (connected either from the top coupler, or from the left port on the bottom) is distributed over 6 ring resonators and a 3-port interferometer. The tested device has a 2μm oxide cladding.

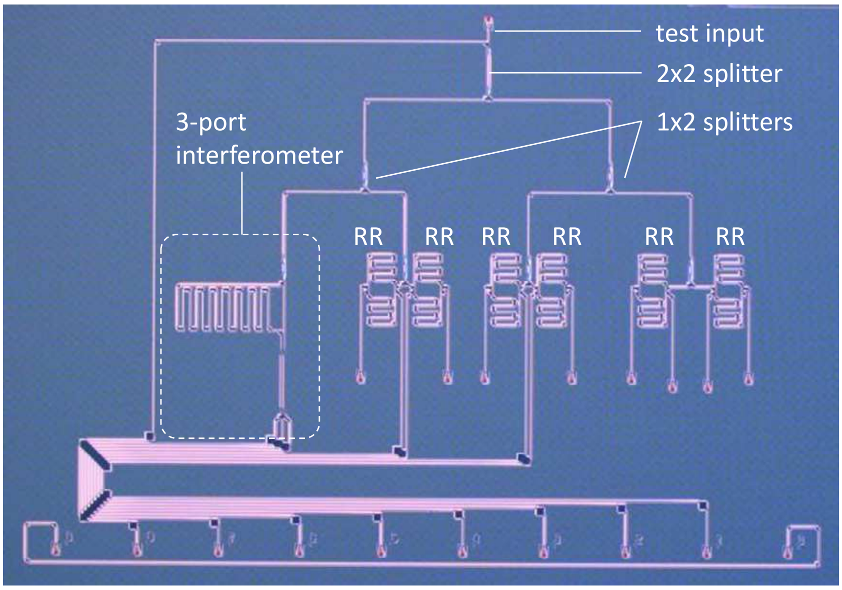

Figure 3. Microscope image of a test circuit consisting of a 3-port interferometer and 6 ring resonators. The grating couplers are arranged at a 250 μm pitch to enable standardized fiber array coupling. The 8 inputs connect to (from left to right) the circuit input, three interferometer outputs, and 4 ring 'through' ports.

The top left graph of Figure 4 shows the normalized response of all three interferometer ports. The expected 120° shift between the channels can be observed. We notice some amplitude variations which are not the same for each channel, possibly caused by inter-interferometer reflections. To correct for this we applied the following procedure for each channel individually:

1. Locate the local minima and maxima
2. Obtain the lower and higher amplitude envelopes by linear interpolation between all minima and maxima, respectively.
3. Correct the data by these envelopes (subtraction and division) to obtain signals between zero and unity.

From this corrected data (Figure 4, top right) we calculate the phase using [3]:

$$\tan(2\pi n\frac{\Delta L}{\lambda}) = -\sqrt{3}\,\frac{I_3 - I_1}{2I_2 - I_3 - I_1}$$

where I_k is the output of channel k, $n\Delta L$ is the optical path length difference, and λ is the wavelength. The result is nearly a straight line (Figure 4, lower left) with deviations less than 1% of the interferometer FSR (Figure 4, lower right).

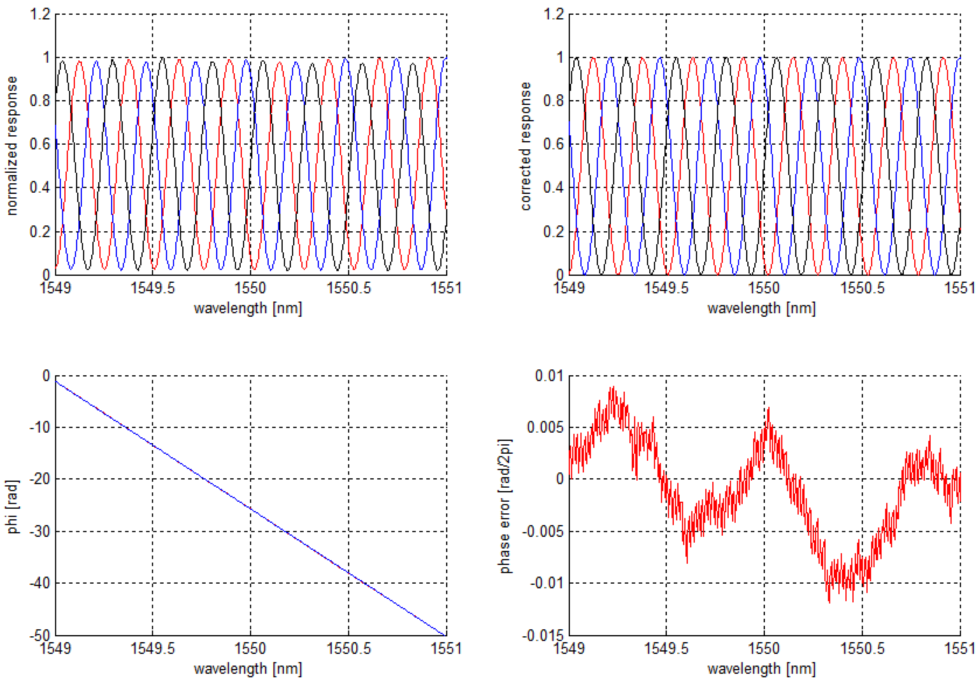

Figure 4. Response of the SOI interferometer. Upper left: normalized data; upper right: corrected data (see text); lower left: phase vs. wavelength and lower right: phase error.

It should be mentioned that for large wavelength spans the quadratic wavelength dependence of the interferometer FSR must be taken into account.

Interferometer in Indium Phosphide

We have also realized similar interferometers in InP active passive technology. Devices were fabricated at Oclaro in the framework of the PARADIGM program [8] (Figure 5). In spite of the high waveguide losses of this particular fabrication run, we obtained again the characteristic 3-port interferometer responses (Figure 6).

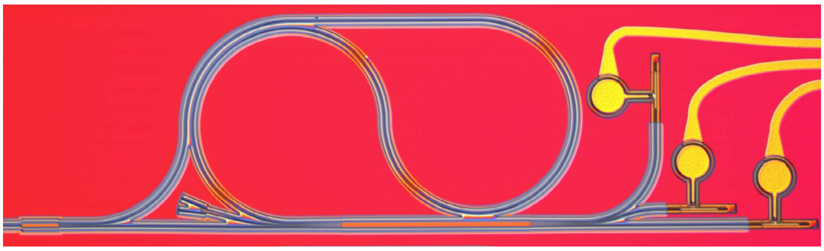

Figure 5. Microscope photograph of 3-port interferometer in InP, having integrated photo diodes.

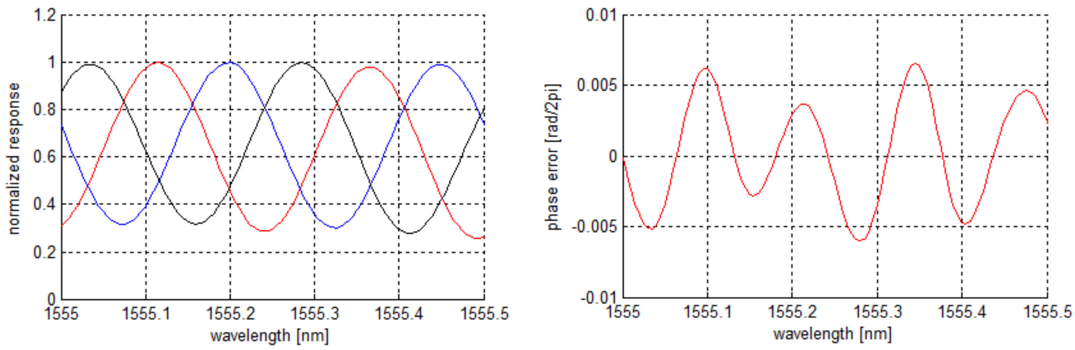

Figure 6. Response of the InP interferometer. Left: normalized data; right: phase error.

Conclusions

We have demonstrated on-chip 3-port interferometers for wavelength tracking, realized both in SOI and InP multi-project wafer services. These interferometers are key building blocks for low-cost on-chip read-out units, in particular for ring resonator based multi-parameter environmental sensors and for biosensors. The concept is robust, yielding 120° phase difference in the three output ports of the 3x3 splitter for both concepts, in spite of high fabrication-induced losses of the InP devices. The measured phase error was less than 1% of the free spectral range, which can be improved by suppressing unwanted reflections.

References

[1] T. Claes, W. Bogaerts, P. Bienstman, "Vernier-cascade label-free biosensor with integrated arrayed waveguide grating for wavelength interrogation with low-cost broadband source", Optics Letters, Vol. 36, No. 17, 2011, pp. 3320-3322.

[2] P. Harmsma, J. Staats, D. Lo Cascio, L. Cheng, "Three-port interferometer in silicon-on-insulator for wavelength monitoring and displacement measurement", Lasers and Electro-Optics Europe (CLEO EUROPE/EQEC), 12th European Quantum Electronics Conference, Munich, May 2011.

[3] J. Pozo, W. Westerveld, P. J.Harmsma, S. Yang, "Silicon on insulator photonic integrated sensors: On-chip sensing and interrogation", 13th International Conference on Transparent Optical Networks (ICTON), pp. 1-4, Stokholm, June 2011.

[4] R. Heideman, M. Hoekman, E. Schreuder, "TriPlex-Based Integrated Optical Ring Resonators for Lab-on-a-Chip Environmental Detection", IEEE JSTQE, Vol. 18, No. 5, pp. 1583 – 1596, 2012.

[5] http://www.epixfab.eu/

[6] X. Leijtens, "JePPIX: the platform for Indium Phosphide-based photonics," IET Optoelectron, Vol 5, No 5, pp. 202-206, 2011.

[7] P. Dumon, W. Bogaerts, R. Baets, J. M. Fedeli, and L. Fulbert, "Towards foundry approach for silicon photonics: silicon photonics platform ePIXfab," Electron. Lett, Vol 45(12), 581-582, 2009.

[8] http://paradigm.jeppix.eu/