Silicon opto-electronic wavelength tracker based on an asymmetric 2x3 Mach-Zehnder Interferometer

José David Doménech(1), Javier S. Fandiño(2), Bernardo Gargallo(2),
Rocío Baños(2) and Pascual Muñoz(1,2)

(1) VLC Photonics S.L., C/ Camino de Vera s/n,
Valencia 46022, Spain e-mail: david.domenech@vlcphotonics.com

(2) Optical and Quantum Communications Group, iTEAM Research Institute,
Universitat Polit`ecnica de Val`encia, C/ Camino de Vera s/n,
Valencia 46022, Spain e-mail: pmunoz@iteam.upv.es.

Abstract

In this paper we report on the experimental demonstration of a Silicon-on-Insulator opto-electronic wavelength tracker for the optical telecommunication C-band. The device consist of a 2x3 Mach-Zehnder Interferometer (MZI) with 10 pm resolution and photo-detectors integrated on the same chip. The MZI is built interconnecting two Multimode Interference (MMI) couplers with two waveguides whose length difference is 56 mm. The first MMI has a coupling ratio of 95:05 to compensate for the propagation loss difference corresponding to the 56 mm. The wavelength tracker design provides three complementary, with 120○ phase relations, responses. The MZI optical responses exhibit rejection as good as 15 dB, thanks to asymmetric design for the input coupler. Synchronized recorded DC electronic responses for the three photo-detector outputs reproduce the MZI de-phased characteristic, allowing for monitoring wavelength changes with sign.

1 Introduction

Wavelength tracking (WVLT) devices are of application in the fields of optical communications, instrumentation and sensing. These devices allow for monitoring changes in the wavelength of an optical signal caused by different phenomena, such as strain, temperature and humidity, among other, as illustrated in Fig. 1- (a). There have been a significant number of WVLT implementations with discrete components, [1] [2] are good examples, and most of the commercial implementations use such assemblies. A versatile well known layout for a WVLT makes use of an imbalanced Mach-Zehnder interferometer (MZI), where each arm of the interferometer has a different length, as shown in Fig. 1-(b).

The imbalanced MZI has a periodic power spectral response that follows a cosine square expression (see theory in [3]). The spectral period, commonly named free spectral range (FSR) is inversely proportional to the length difference between the two arms of the MZI. To be precise, $\mathrm{FSR} = \lambda^2/(n_g \Delta L)$, where is the operating wavelength, n_g is the group index for, and ΔL is the length difference between, the arm waveguides. Furthermore the MZI can be integrated on a photonic chip, with photo-detectors. MZI based WVLTs can make use either of 2 or 3 complementary outputs. The former usually provides outputs with a phase relation of 180°, whereas the latter are commonly designed for the optical outputs to have phase relations of {–120°, 0°, 120°}. While both configuration allow for monitoring the change in wavelength through the relative power change between the output signals, the 3 output port configuration enables to determine the sign of change as well. Integrated WVLT MZIs based on Multimode Interference (MMI) couplers have been reported in different technologies, and a remarkable layout for Silicon-on-Insulator (SOI) technology is proposed in [4], where Harmsma and co-workers made a 2x3 MZI SOI device with 0.55 nm FSR.

In this paper we report on the experimental demonstration of a WVLT photonic chip based on a 2x3 MZI with integrated photo-detectors (PDs) in SOI technology. The device has a FSR of 10 pm and a footprint of 2.5×0.5 mm^2.

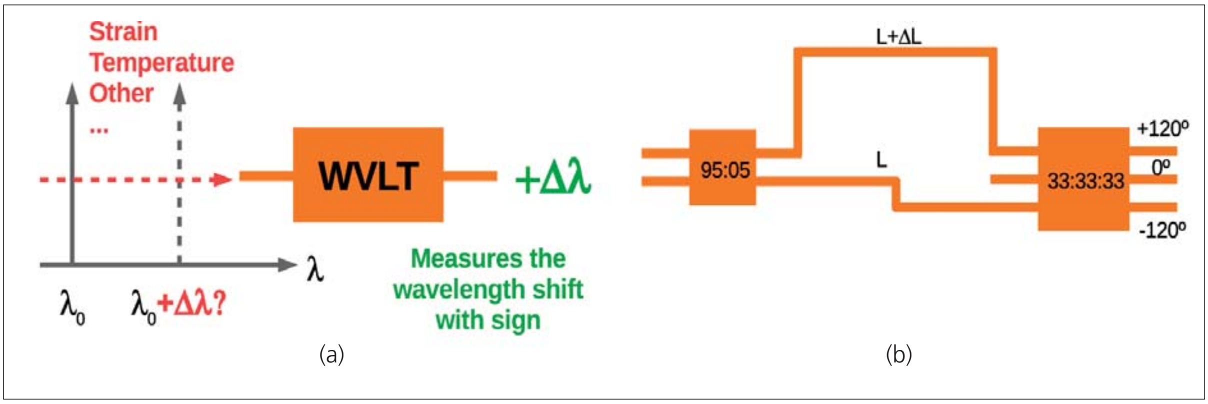


Figure 1. Wavelength tracker concept (a) and sketch of a 2x3 Mach-Zehnder Interferometer based on Multimode Interference couplers (b).

The paper is structured as follows. Section 2 reviews the design and fabrication of the MMIs. Section 3 describes the design and experimental demonstration of the WVLT. The conclusion and outlook are given in Section 4.

2 Multimode Interference couplers

The MMI couplers can be designed for an arbitrary coupling ratios following the design rules by Besse and coworkers [5], and supported by Beam Propagation Method (BPM) commercial software optimizations [6]. Full details are given in our previous work [7].

The design of all the MMIs was carried out in three steps: i) cross-section analysis and 2D reduction, ii) analytical approach and iii) numerical BPM optimization. The cross section consists of a buried oxide layer of 2 microns height, capped with a 220 nm Si layer and a SiO_2 overcladding. Rib waveguides, with 130 nm etch depth from top of the Si layer, were used in the design stage.

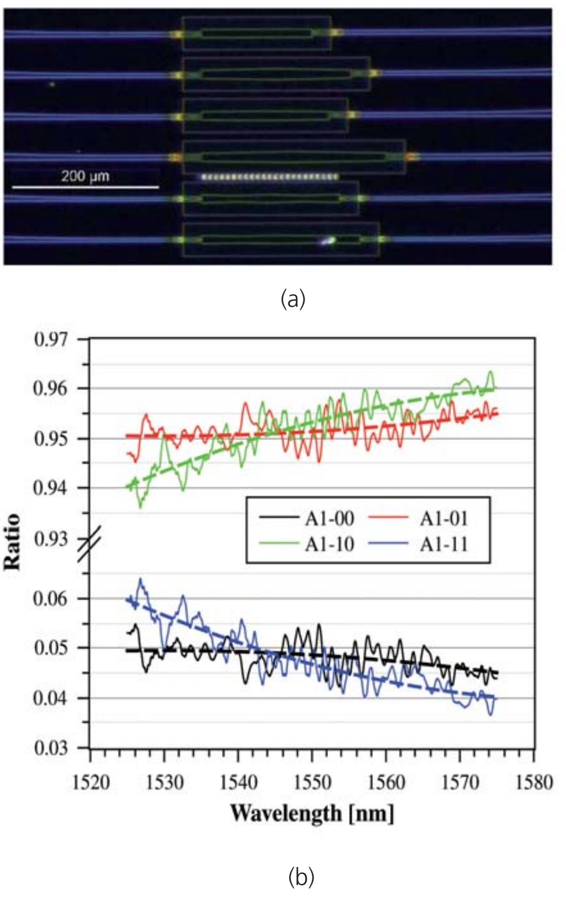
Firstly, for the cross-section analysis a film-mode matching mode solver was used [6]. For a given MMI width, the first and second mode propagation constants, β_0 and β_1 respectively, were found for a wavelength of 1.55 μm for TE polarization, and the beat length $L_\pi = \pi/(\beta_0 - \beta_1)$ was computed from these. For the case of all the MMIs subject to design, the body width was set to 10 μm. The effective indices for the first and second mode given by the solver are $n_{eff,0}$=2.84849 and $n_{eff,1}$=2.84548. Therefore the beat length results into L=257.61 μm. Secondly, analytic design rules for canonical [8] and arbitrary coupling ratio [5] MMIs were used. These rules provide, for a given MMI width, an analytic approximation for the MMI body length, named L^0, from the previously calculated L_π, and for the case of arbitrary ratio, the width variation and body geometry (named type A, B, B symmetrized, C and D in [5]). The analytic approximations for the 95:05 MMI lengths is:

$$L^0 = \delta_W \frac{1}{3}(3L_\pi) \quad (1)$$

where $3L_\pi$ is the distance for the first direct (not mirrored) image [8] and $\delta W = 1 - 2\Delta W/W$, with W the MMI body width and ΔW the MMI body widening/narrowing.

The final step consists of using BPM for a MMI having input/output tapered waveguides. Tapers are required to minimize the MMI excess loss, imbalance and reflections as described in [9] [10]. Hence, BPM is used to find iteratively both the MMI length and the input/output tapers width. The optimization process has as target to minimize the coupler imbalance, i.e. that the ratios at both outputs match the target, and to maximize the overall optical power with respect to the input, i.e. to minimize the excess loss. The optimization process starts with a fixed set of taper width and MMI length. The starting taper width was set to 3 μm. The taper length was set to 50.0 μm, which is sufficiently large for adiabatic linear tapering as per [?]. The MMI length was set to the values obtained through the aforementioned analytic formulas. They provide an MMI length that does not account the tapering of the input/outputs, which in turn modifies the propagation conditions in the multimode waveguide. Therefore, for the initial guess of taper width, the length of the MMI is solved numerically in a first step. Next, the width of the taper is varied. Both parameters are iteratively changed following update and minimization numerical methods commonly now, until a solution is found for the coupling ratios, having as stop condition a tolerance of 0.01. The optimization was performed firstly for λ= 1.55 μm, and finally cross-checked for the design wavelength interval, 1.525-1.575 μm.

The MMI devices were fabricated in a multi-project wafer technology at the Institute of Microelectronics of Singapore [11]. A photograph of the fabricated devices is given in Fig. 2-(a). The coupling ratio for the 95:05 device is plotted in Fig. 2-(b).The results show good agreement with target coupling ratios, where deviations are approximately in the range of ±0.01. Further details on fabrication reproducibility between dies and wafers is supplied in [7].

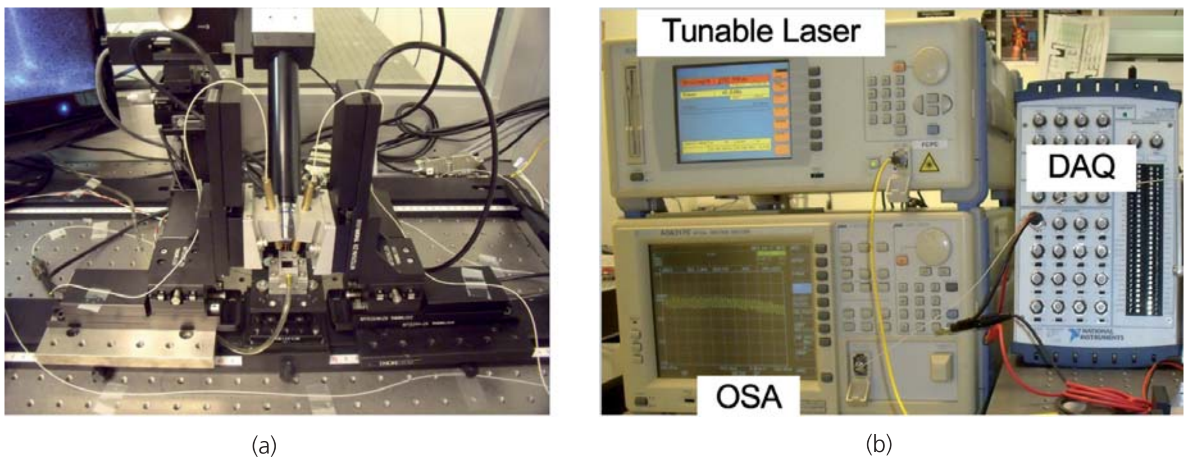


■ **Figure 2.** Multimode Interference coupler fabricated devices (a) and C-band characterization of the 95:05 coupler (b).

3 MZI wavelength tracker

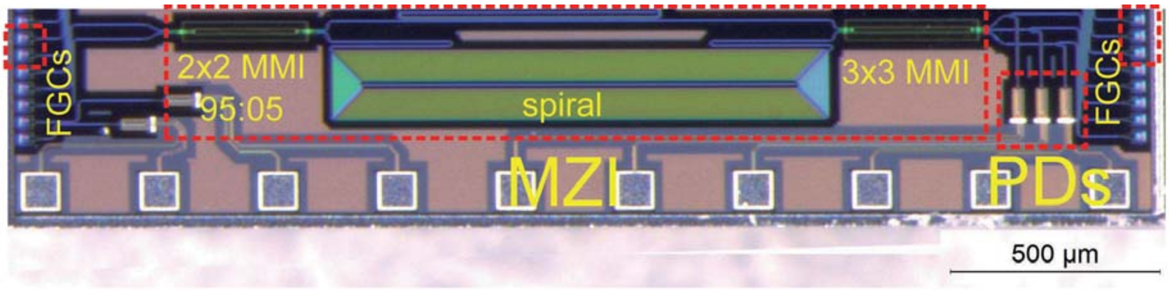
The WVLT was designed for, and fabricated in, a multi-project wafer technology by the OpSIS platform at IME Singapore as the MMIs. The process allows for passive and opto-electronic active areas, as p-n junction modulators and photo-detectors. An optical microscope picture of the device is given in Fig. 4-(a). The device is composed of a 2x2 MMI input coupler and a 3x3 MMI output coupler. The couplers are designed in a shallowly etched areas, and designed following the rules in [8]. The output coupler has a 33:33:33 coupling ratio. The inputs/outputs to the couplers are tapered and all the dimensions were numerically optimized using a Beam Propagation Method (BPM) commercial software [6]. The two outputs of the first coupler are connected to the top and bottom inputs of the output coupler with strip waveguides of 450 nm width. One of the connections is a straight waveguide, whereas the other is a spiral waveguide of 56 mm, which for a group index of 4.25 corresponds to a FSR of 10 pm. The input coupler is designed to have a 95:05 coupling ratio, so as to compensate the large loss imbalance between the short and long arm, in order to attain the maximum rejection in the MZI spectral response. The output coupler outputs are connected to Y-branches. One output of each Y-branch is connected to a PD, and the other is used as test optical output. Focusing grating couplers (FGCs) are used as light input/output structures.

The chip was held in a vacuum chuck, whose temperature was kept to 25° C using a temperature controller (TEC). Fibers, at angle of 74° from the chip normal, were aligned to the input/output FGCs using motorized translation stages, as shown in the photograph of Fig. 3-(a). Firstly, the spectral response of the MZI was measured. A tunable laser source synced with an an Optical Spectrum Analyzer (OSA) was used to acquire traces with 1 pm resolution. The traces, normalized with respect of a straight waveguide, are shown in Fig. 4- (b) for a wavelength interval around 1549.83 nm for the three outputs labeled 0, 1 and 2 in the figure. The spectral displacement between the traces correspond approximately to one third of the FSR, in agreement with the designed phase relations for the output MMI coupler. Despite the chip temperature was controlled, we observed spectral drifts of ±1 pm in the measurements from a nominal position, in the scale of se-

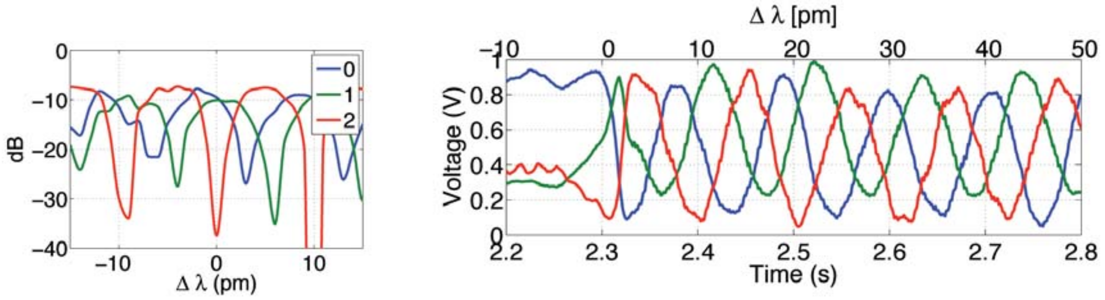


(a) (b)

■ **Figure 3.** Vertical fiber characterization setup (a) and tunable laser, optical spectrum analyzer and data acquisition module (b) photographs.



(a) Optical microscope image of the fabricated devices



(b) Optical I/O MZI response

(C) Opto-electronic synchronized response

Figure 4. Optical microscope image of the fabricated device (a) MZI I/O spectral traces with respect of 1549.83 nm (b) and synchronized electronic traces (c) for the three WVLT channels.

veral tens of seconds, which we attributed to the limited resolution of the TEC. The rejection ratio attained in all the responses, defined as the difference between maximum and minimum value in a period, is at least around of 15 dB, thanks to the asymmetric input MMI coupler.

Secondly, the setup was conditioned to measure the opto-electronic response of the WVLT. Probes were used to contact the PD pads, Fig. 4-(a) lower right corner. Each probe was then loaded with a 10 k resistor, and the PDs were biased at -2V. In absence of optical input we observed a dark current of 2 μA. The three resistors where then probed and connected to three channels of a data acquisition (DAQ) card, which allows for recording simultaneously the voltage corresponding to the current change in the three PDs. A tunable laser (TL) was then used as input, to be swept in steps of 1 pm. A photograph of the setup is shown in Fig. 3-(b). Furthermore, LabViewTM programs were deployed to control simultaneously the TL sweep and the DAQ recording, in order to obtain synchronized data at all the outputs. The results are shown in Fig. 4-(c). They correspond to smoothed data using a moving average of 10 points. The TL start and end wavelengths were set to 1550 nm and 1550.090 nm respectively, and the sweep was started iteratively. The traces in (c) are shown in a given time where, on the left hand side, the currents acquired have random value, since the TL is returning to the start wavelength. After this period of time (around 2.3 s in the figure) the sweep starts and the voltages recorded reproduce the sinusoidal variation of (b), with a one third period de-phased relation as well. Panel (c) top axis shows the sweep time translated into wavelength change from 1550 nm (negative values are arbitrarily labeled to represent the TL return time).

4 Conclusion and outlook

In conclusion, we have reported the experimental demonstration of a SOI opto-electronic wavelength tracker. The device is based in a 2x3 Mach-Zehnder interferometer, with 10 pm resolution, equipped with photodetectors. The optical transfer function exhibits the phase relations of one third of the FSR, as expected from the design of the output MMI coupler. The optical rejection attained is at least as good as 15 dB. The opto-electronic transfer functions, recorded synchronously at the photo-detectors, reproduce the targeted tracking responses.

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Biographies

José David Doménech was born in Alfafar, Valencia (Spain). He received the B.Sc. degree in Telecommunications from the Escuela Politécnica Superior de Gandia (EPSG), Valencia, Spain, in 2006, the M.Sc. degree in Technologies, Systems and Networks of Communication from the Universidad Politécnica de Valencia (UPV), Valencia, Spain, in 2008 and the Ph.D. degree in photonics in 2013 at the Universitat Politècnica de València within the Optical and Quantum Communications Group. He has been involved in several national and international research projects. He has published over 10 papers in international refereed journals and over 20 conference contributions. J.D. Doménech received the Intel doctoral student honor programme award in 2012 in recognition for his work during his Ph.D. He is co-founder and CTO of the spin-off company VLC Photonics, devoted to the design of photonics integrated circuits in multiple integration technologies.

Javier S. Fandiño was born in Orihuela (Alicante), in 1987. He received the bachelor degree in Telecommunications engineering and the M.S. degree in Technology, Systems and Telecommunications Networks, both from the Universidad Politécnica de Valencia (Spain), in 2010 and 2011, respectively. In 2011, he joined the Optical and Quantum Communications group (GCOC), where he was first engaged in the experimental demonstration of an all-optical 2R regenerator for extended PON networks. At present, he is currently pursuing his PhD in telecommunications engineering in the GCOC, supported by the Spanish Ministry of Science and Innovation trough a FPU (Formacin de Personal Universitario) scholarship. His research topics include design and characterization of photonic integrated circuits (both in Silicon-On-Insulator and InGaAsP), and their potential applications in coherent optical communications and microwave photonics.

Bernardo Gargallo was born in Valencia, Spain, on August 29th, 1986. He received the M.Sc. in Telecommunication Engineering from the Universitat Politècnica de València (UPV) in 2011. He is currently pursuing the Ph.D. Degree at the Optical and Quantum Communications Group (OQCG), ITEAM Research Institute, UPV. His research has been focused on the design of integrated optical circuits to be applied in coherent communications, spectrometry and signal analysis.

Rocío Baños was born in Albacete, Spain, on 1986. She received the M.Sc. in Telecommunication Engineering from the Universitat Politècnica de València (UPV) in 2010. She is currently pursuing the Ph.D. Degree at the Optical and Quantum Communications Group (OQCG), ITEAM Research Institute, UPV. Her research has been focused on the design of fiber Bragg grating and integrated optical circuit based encoders to be applied in optical code division multiplexed networks. From 2014, she is in charge of the photonic integrated circuits laboratory at OQCG.

Pascual Muñoz was born in Valencia, Spain on February 7th, 1975. He received the Ingeniero de Telecomunicación degree from Universitat Politécnica de València (UPV) in 1998. In 1999 he served as 1st Lieutenant in the Spanish Airforce, while working as IT consultant for AIME Instituto Tecnológico. He received a Ph.D. degree in photonics from UPV in 2003. He is currently Associate Professor at the Departamento de Comunicaciones, and researcher at the Institute for Telecommunications and Multimedia Applications (ITEAM), both at UPV.

Dr. Muñoz runs a consolidated research line, started in 2005, on prototyping Photonic Integrated Circuits (PICs) in a technology agnostic fashion, where PICs are designed in the best suited technology (Silicon-On-Insulator, Indium Phosphide, Silica on Silicon, Silicon Nitride amongst other) for each application. He has been involved in several European Commission funded projects, being coordinator for integration on InP within the NoE IST-EPIXNET. He has published over 25 papers in international refereed journals and over 40 conference contributions. He is a member of the Technical Programme Committees of the European Conference on Optical Communications (ECOC) and the European Conference on Integrated Optics (ECIO). Dr. Muñoz received the VPI Speed Up Photonics Award in 2002 for innovative Fourier optics AWG with multimode interference (MMI) couplers modeling, by Virtual Photonics Incorporated and IEEE Communications Magazine. He was also granted the IEEE/LEOS Graduate Student Fellowship Program in 2002. He received the extraordinary doctorate prize from UPV in 2006. From his research line, he co-founded the UPV spin-off company VLC Photonics in 2011, where the PIC design know-how, expertise and tools have been transferred, and he served as CEO from 2011 to 2013. Dr. Muñoz is a Senior Member of IEEE and Member of the OSA.