2.3 µm wavelength range digital Fourier transform on-chip wavelength monitor

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Abstract: We present a novel approach for on-chip wavelength monitoring based on a digital Fourier Transform spectrometer. We demonstrate 130 nm operational bandwidth and an accuracy of 100 pm in the 2.3 µm wavelength range.

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1. Introduction

The rising interest in the mid-IR for spectroscopic sensing has fostered a large amount of work in recent years towards more compact, sensitive and cost-effective systems. One of the essential components of many sensing systems consists of a spectrometer, which allows to separate optical beams of different wavelengths. Common integrated spectrometer solutions are based on echelle gratings and arrayed waveguide gratings (AWGs). However, these approaches have an intrinsic limitation related to their footprint/resolution trade-off as for a given bandwidth the resolution scales inversely linearly with the device footprint [1]. This makes these spectrometers not very appealing for applications such as wavelength monitoring.

A novel approach, named digital Fourier Transform (dFT) spectrometer, that overcomes this limitation, has been recently proposed [2]. This approach is based on a cascade of Mach-Zehnder interferometers (MZIs), which are sequentially thermo-optically switched in a binary way (see Fig. 1(a)). Every MZI in the cascade is followed by a delay line pair and, depending on the switch state, light is sent to one of the delay lines. The MZI switches are inserted in a main MZI. At the device output light will interfere with an optical path delay (OPD) which is the difference between the optical paths of the 2 arms of the main MZI for a given configuration of switch states. In such case, the equivalent number of channels scales exponentially with the number of optical delay pairs [1]. The dFT spectrometer allows also to utilize only a single photodetector (PD), differently from classical AWG and echelle configurations with integrated detector arrays. This dFT approach has been recently demonstrated for spectrally broad input signals [1]. However, there are several applications such as wavelength monitoring in tunable laser systems or Raman spectroscopy which would benefit from systems able to identify only a very small set of discrete lines. Hence, we decided to investigate the dFT approach for spectrally sparse input signals. This choice allows to achieve a very broadband behavior because of the removal of artifacts, to reduce the computation time and to enhance the device robustness. Besides, the number of optical delay pairs may be reduced when using compressive sensing techniques without a loss in performance [3].

2. Design, fabrication and experimental results

The design is based on a 3-stage architecture as shown in Fig. 1(a) working around 2.3 µm wavelength because of its relevance for spectroscopic sensing applications [4]. The minimal OPD length $\Delta L = 10.825\mu$m is obtained from [1]:

$$\delta\lambda \approx \frac{1}{2^N}\frac{\lambda^2}{n_g \Delta L} \tag{1}$$

where $\delta\lambda$ set to 2 nm is the channel bandwidth and $N = 6$ is the number of OPD pairs. Every stage ($k = 1,2,3$) has a top and a bottom arm with same spiral lengths $L_k = L_1 + 2^{2k-2}\Delta L$ where L_1 is a minimal length given by spiral design constraints. The increment of OPD for the top arm is $2^{2k-1}\Delta L$, while for the bottom arm it is $-2^{2k-2}\Delta L$ with respect to the common arm length of each delay line pair. Grating couplers are used for in/out light coupling. The design presents 2 outputs to integrate at a later stage a PD by e.g. flip-chip technology, while at the same time still being able to fiber-monitor the complementary output. The working principle consists of acquiring a calibration matrix A by scanning all the different 64 configurations of switch states as a function of the wavelength sampling/grid points. In such case the overall system can be represented with a linear relation $y = Ax$ where x is the unknown wavelength vector (weight of the different input wavelengths on the wavelength grid) and y is the data recorded from the PD for the different switch configurations. Several techniques can be exploited to solve such problem depending on the signal input. By using the information on the sparse character of the input signal, the convex optimization problem can be solved using the efficient least absolute shrinkage and selection operator (LASSO) instead of more general methods such as the Moore-Penrose least-squares (LSQR) inverse. The latter has also disadvantages in terms of accuracy and operation bandwidth [1,3]. The fabrication is based on a Silicon-

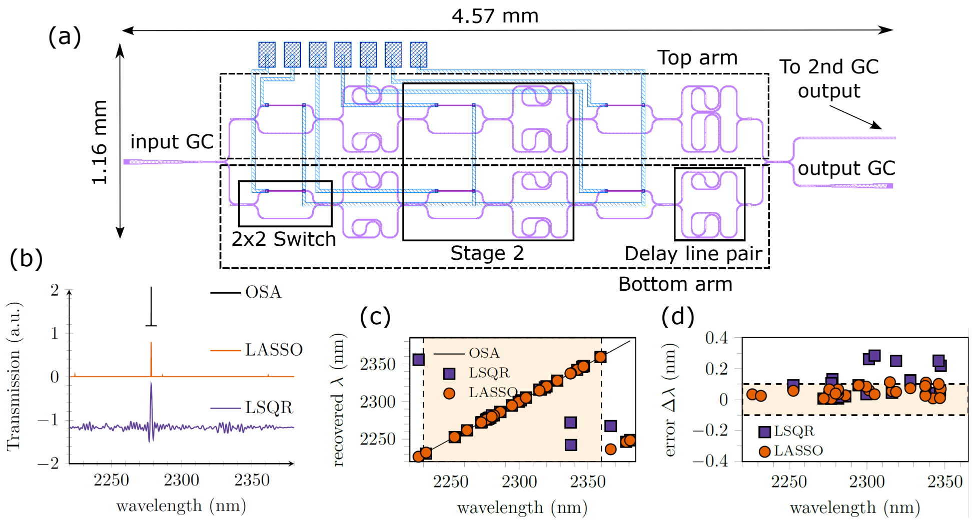

Fig. 1. Layout and performance of the 3-stage dFT spectrometer. (a) Layout view. A second complementary grating coupler output for later PD integration has been omitted for clarity. (b) Example of line retrieval compared to the OSA reference using 2 different methods: LSQR and LASSO. (c) Line retrieval positions using LASSO and LSQR methods. The latter provides outliers also in the operation bandwidth. (d) Error for the different methods, obtained by choosing random wavelengths.

on-Insulator (SOI) platform with 400 nm Si device layer thickness. A 180 nm partial etch is used to define rib waveguides and gratings by ebeam lithography and reactive ion etching. A SiO_2 layer is deposited to enable Ti-based heater fabrication above waveguides and related Ti/Au pads. The minimum feature dimensions of the dFT circuit are chosen such that all the fabrication can in principle be carried out using industry-standard silicon tools. The setup is based on a Yokogawa AQ6375 optical spectrum analyzer to record the spectrum and an IPG photonics SFTL-Cr-ZnS/Se laser as source. The chosen wavelength grid for the calibration was 500 pm. The accuracy of the spectral recovery was further increased by interpolating the calibration matrix on a finer 50 pm grid. Therefore the number of wavelength points was 3200 for a 160 nm span. Fig. 1(b) reports an example of wavelength recovery for the 2 methods (LASSO and LSQR). The LASSO method clearly shows a cleaner retrieved spectrum over the bandwidth of operation. We demonstrate correct wavelength recovery over the entire 130 nm bandwidth of the spectrometer (see Fig. 1(c)) and an accuracy of 100 pm is achieved as shown in Fig. 1(d). The LSQR method tends to produce consistently a larger error and thus it is not as suitable for sparse input signals.

3. Conclusions

We demonstrated a Si photonics dFT spectrometer for wavelength monitoring. We show an accuracy of 100 pm over a bandwidth of 130 nm for a device with 5.3 mm^2 footprint working in the 2.3 μm wavelength range.

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