Spatial Heterodyne Fourier-Transform Spectrometer Implemented With Silicon Wire Spiral Waveguides

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Abstract—**The design, fabrication and characterization of a Fourier-transform planar waveguide microspectrometer are presented. The device comprises an array of 32 Mach-Zehnder interferometers with increasing optical path differences between arms across the array, achieving a wavelength resolution of 0.1 nm within a free spectral range of 1.6 nm. Spiral Si-wire waveguides are used in the arms of the interferometers in order to reduce the footprint of the device to less than 12 mm^2.**

Keywords- spatial heterodyne spectroscopy; silicon-on-insulator waveguides; Fourier-transform spectrometer

I. INTRODUCTION

Compact high-resolution spectrometers and multiplexers are required for a wide range of applications such as optical communication networks, health diagnosis, environmental sensing and space instrumentation, to name a few [1]. Arrayed waveguide gratings (AWGs) can achieve sub-nanometer resolution [2], but require a single mode input waveguide, which largely limits their optical throughput (*étendue*), which is critical when spatially extended and incoherent sources are analyzed. Planar waveguide Fourier-Transform spectrometers based on the principle of Spatial Heterodyne Spectroscopy (SHS) have been recently propose to overcome this *étendue* limitation [3,4]. SHS is an interferometric technique based on the Michelson interferometer [5], and in which moving mirrors are replaced by diffraction gratings [6]. The SHS concept can be implemented by a waveguide array of Mach-Zehnder interferometers (MZI) with increasing path differences [3,7]. Full spectrum analysis within the free spectral range of the device is performed in a single measurement, by Fourier analysis of the output stationary interference pattern.

In this work, we present a SHS-FT spectrometer with enhanced resolution in a small footprint by implementing tightly coiled spiral waveguide structures in a MZI array.

II. PRINCIPLE OF OPERATION

Our Fourier-transform spectrometer comprises an array of N silicon wire waveguide MZIs with an increasing path length difference ΔL_i, which is achieved by combining in each MZI an arm with a straight waveguide and another arm with a spiral waveguide. Thanks to the high contrast index of the silicon-on-insulator (SOI) platform, spirals with high path lengths can be implemented in a reduced diameter of a few hundred micrometers. For a given input spectral distribution, the dispersive nature of the MZIs produces a wavelength-dependent oscillatory pattern (interferogram $F(x_i)$) at the outputs of the array, allowing to retrieve the full input spectrum p_{in} by discrete Fourier cosine transform of the interferogram:

$$p_{in}(\bar{\sigma}) = \frac{\Delta x_{\max}}{N} P_{in} + 2\frac{\Delta x_{\max}}{N}\sum_{i=1}^{N} F(x_i)\cos 2\pi\bar{\sigma}x_i \qquad (1)$$

where x_i is the path delay of the i-th MZI, Δx_{max} is the maximum optical path difference, P_{in} is the input power, and $\bar{\sigma} = \sigma - \sigma_L$ is the shifted wavenumber, relative to the Littrow wavenumber σ_L. The resolution $\delta\lambda$ and free spectral range $\Delta\lambda$ of the spectrometer are determined by $\delta\lambda = \lambda_0^2/(\Delta L_{max}\times n_{eff}) = 2\Delta\lambda/N$, where λ_0 is the spectrometer central wavelength and n_{eff} is the effective index of the waveguide mode.

The distortion of the interferogram, produced by different propagation losses across the MZI array and phase errors arising from fabrication imperfections, need to be calibrated and corrected in the spectral retrieval algorithm.

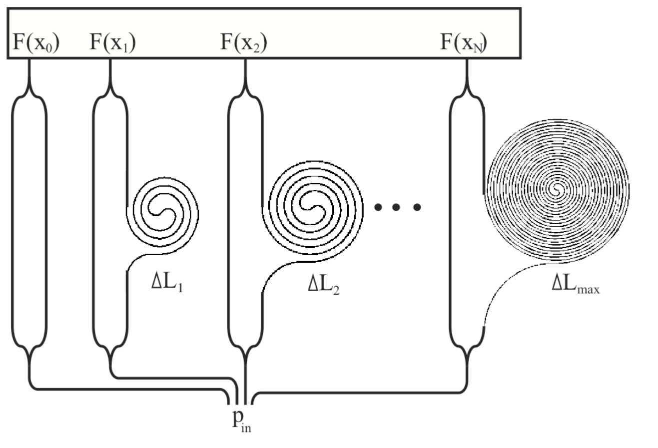

Figure 1. Schematic of the Fourier-transfrom spectrometer.

III. DESIGN AND FABRICATION

The SHS-FT spectrometer comprises 32 MZIs with a maximal physical length difference ΔL_{max} = 1.13 cm. With an estimated effective index of n_{eff} = 2.12 for TM polarization at a central wavelength of 1.55 µm, the device is designed for a resolution of 0.1 nm and a free spectral range of 1.6 nm. To simplify optical measurements, a single input was used, followed by cascaded 1:2 *y*-splitters. Efficient subwavelength grating couplers [7] were included both at the input and the outputs of the chip.

Samples were fabricated on SOI substrates with a 0.26 µm thick silicon and a 2 µm thick buried oxide (box) layers. All structures were defined in a single patterning step by electron beam lithography with high contrast hydrogen silsequioxane (HSQ) resist, and transferred into the silicon layer by inductively coupled plasma reactive ion etching (ICP-RIE).

IV. EXPERIMENTAL RESULTS

The fabricated device was thermally stabilized using a Peltier stage and the output interferogram was characterized using a high-resolution tunable semiconductor laser over the range 1549 nm - 1551 nm, with a wavelength step of 1 pm (Fig. 2). A polarization controller was used to select TM input field. Phase errors and propagation loss were characterized by fitting the output wavelength-dependent signal at each MZI to a sinusoidal function, and corrected in the spectral retrieval algorithm. Experimental results show an average effective index of 2.18 with variations under 1% among the MZI array.

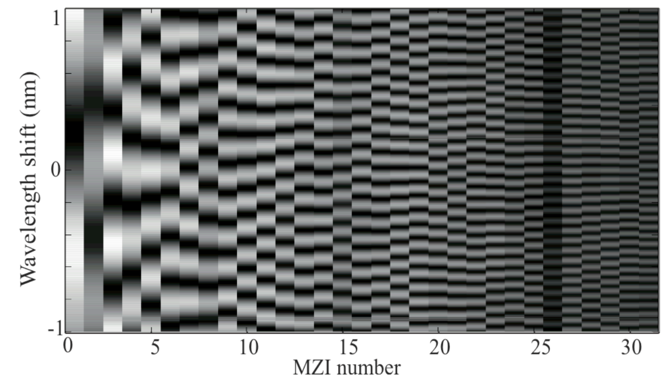

Figure 2. Output power distribution of the 32 MZI for a 2 nm wavelength scan centered at 1.55 µm.

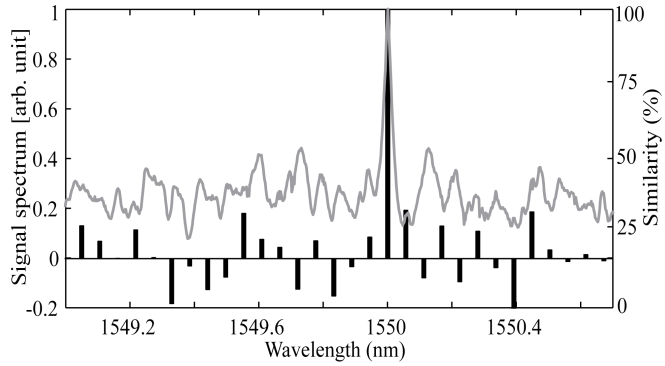

Figure 3. Measured spectral search similarity of a narrowband source centered at 1550 nm (gray), and Fourier-based retrieved spectrum (black).

The device was tested with two different types of numerical analysis of the output pattern (Fig. 3). First, a spectral search technique was used, comparing the measured interferogram with patterns obtained for different wavelengths during the calibration step [9]. Second, a Fourier-based spectral retrieval was used. The oscillations at the output of each MZI from the calibration step were used to define a $N\times N$ transformation matrix T such that $F(x)=p_{in}\times T$, taking into account the measured phase and amplitude errors. The discrete input spectrum of the actual measurement was obtained by multiplying the output pattern by a pseudoinverse T^{+} of the transformation matrix.

V. CONCLUSIONS

A planar waveguide Fourier-transform spatial heterodyne spectrometer has been demonstrated for the first time in silicon wire waveguides. The spectrometer comprises an array of unbalanced Mach-Zehnder interferometers with spiral waveguide delays. Phase errors and propagation losses of the MZI array were characterized and compensated. The use of tightly coiled spiral waveguides allows a high spectral resolution of 0.1 nm for a device footprint of only 12 mm^2. The potential applications include disposable biological and environmental sensing, hand-held spectroscopic instrumentation, and sensing from microsatellite platforms.

ACKNOWLEDGMENTS

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