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Multiaperture Fourier transform arrayed waveguide spectrometer

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Abstract. *We present a new Fourier transform waveguide spectrometer concept based on Mach-Zehnder interferometer arrays. Multiaperture input provides a markedly increased optical throughput. Unlike conventional FT spectrometers, the device has no moving parts. Phase and amplitude errors can be readily measured in this device and numerically corrected with no need for costly modifications of the waveguide physical properties. An example of the spectrometer designed for the silicon-on-insulator platform with sub-nanometer resolution is discussed.*

Introduction

Waveguide spectrometers such as waveguide echelle gratings and arrayed waveguide gratings (AWGs) [1] are key devices in optical telecommunication networks. New applications are emerging, including spectroscopy, environmental sensing, and health diagnostics. In spectroscopic applications, a common figure of merit to be maximized is the optical throughput, or *étendue*. Large *étendue*, also referred to as the Jacquinot advantage [2], is an intrinsic property of a Michelson interferometer. This is also one of the main reasons why Fourier transform (FT) Michelson interferometers are currently dominating the field of infrared spectroscopy.

In order to exploit the *étendue* benefit of the Michelson interferometer, we proposed the first Fourier-transform Michelson-type arrayed waveguide grating (AWG) spectrometer [3]. This device further develops the concept by Harlander et al. who proposed replacing the mirrors in a Michelson interferometer by bulk optics diffraction gratings, which results in an obvious *étendue* benefit [4, 5]. Compared to a conventional AWG which is a generalized multi-path Mach-Zehnder interferometer, an FT AWG, as a Michelson-type device, allows for a larger *étendue*. Furthermore, unlike the conventional Fourier-transform Michelson spectrometer which requires moving parts (a scanning mirror), the FT AWG is a static device obviating the need for scanning elements.

To further increase the spectrometer light throughput, we have recently extended the FT AWG concept into configurations with multiple input apertures [6, 7]. In this paper, we present a multiaperture spectrometer based on an array of Mach-Zehnder interferometers. We discuss device fundamentals and also include an example of spectral retrieval for the application in spatial heterodyne observations of water (SHOW) experiment.

Multi-aperture FT Mach-Zehnder interferometer array

The Mach-Zehnder interferometer is an established device both in bulk optics and waveguide implementations. It has periodic transmission characteristics which is a function of the optical path difference between the two interferometer arms. We use this fundamental property of periodic MZI transmission to form a new type of spectrometer. The spectrometer comprises an array of independent MZIs with different phase delays, as shown schematically in Fig. 1 (left panel). It has a multiaperture input formed by N waveguides each feeding into an individual MZI. An obvious advantage of this device is that the optical throughput is significantly increased by using multiple inputs simultaneously.

The operating principle of the device is as follows. The path difference ΔL_i in the MZI array changes by a constant increment across the array. For a given monochromatic input, different transmission characteristics of each MZI results in a different power value at its output. A monochromatic input results in a periodic (sinusoidal) spatial distribution of power across the different output ports $P^{out}(x_i)$, which is the Fourier-transform of the monochromatic input spectrum. Since the spatial power distribution $P^{out}(x_i)$ and the input spectrum are a Fourier transform pair, a polychromatic input produces a power distribution from which the input spectrum can be calculated using Fourier transformation.

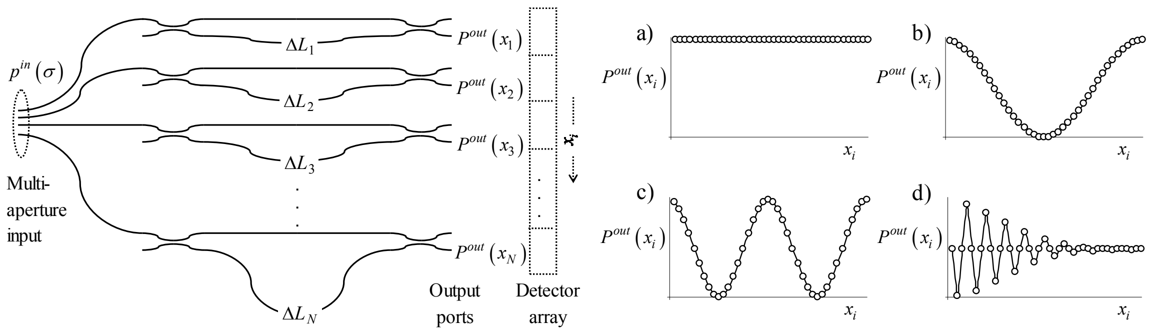

Fig. 1. Left: The schematics of the waveguide spectrometer formed by arrayed Mach-Zehnder interferometers. Right: Spatial fringe formation at the arrayed MZI outputs corresponding to monochromatic inputs at a) the Littrow wavenumber σ_L, b) $\sigma_L+\delta\sigma$, c) $\sigma_L+2\delta\sigma$, and d) superposition of monochromatic inputs.

The MZI array can be designed such that for a particular monochromatic input of a wavenumber $\sigma_L=1/\lambda_L$, a constant spatial power distribution $P^{out}(x_i)$ is obtained at the output, as shown in Fig. 1a. This we denote as the Littrow condition, with the zero spatial frequency corresponding to the Littrow wavenumber σ_L. For $\sigma = \sigma_L$, the phase delays in different MZIs are integer multiples of 2π resulting in constant output spatial power distribution. As the wavenumber of the monochromatic input σ changes from the Littrow value, the output power distribution becomes periodic with the spatial frequency, increasing with $|\sigma-\sigma_L|$. Changing the wavenumber from the Littrow condition to $\sigma_L+\delta\sigma$, where $\delta\sigma$ is the instrument resolution, results in one spatial fringe along the output ports as shown in Fig. 1b. The number of fringes further increases with the increasing wavenumber (Fig. 1c). For a polychromatic signal, a corresponding interferogram is formed by superposition of the respective periodic fringes, as illustrated in Fig. 1d. The input power spectrum can be calculated from the measured interferogram using the discrete Fourier cosine transform [6]:

$$p^{in}\left(\bar{\sigma}\right) = \frac{\Delta x}{N} P^{in} + 2\frac{\Delta x}{N}\sum_{i=1}^{N} F(x_i)\cos 2\pi\bar{\sigma}x_i \qquad (1)$$

where $F(x_i)$ is the measured interferogram, discretized at N equally spaced values of the spatial coordinate x_i corresponding to the outputs of different MZIs, P^{in} is the total input power, and $\bar{\sigma} = \sigma - \sigma_L$ is the normalized wavenumber shifted with respect to the Littrow wavenumber σ_L.

It can be shown [6] that the wavenumber resolution $\delta\sigma$ of the spectrometer is determined by the maximum interferometric delay ΔL_{max}, that is, the delay corresponding to the most unbalanced MZI in the array. A useful expression for ΔL_{max} can be obtained in terms of the resolving power $R = \lambda_0/\delta\lambda$:

$$\Delta L_{max} = \frac{1}{\delta\sigma n_{eff}} = R\frac{\lambda_0}{n_{eff}} \tag{2}$$

where λ_0 is the spectrometer central wavelength and n_{eff} is the waveguide mode effective index. The minimum number of discrete points N in the interferogram, that is the number of MZIs in the array, can be found from the Fourier sampling theorem:

$$N_{min} = 2\Delta x\,\Delta\sigma = 2\frac{\Delta\sigma}{\delta\sigma} = 2\frac{\Delta\lambda}{\delta\lambda} \tag{3}$$

where $\Delta\lambda$ (or $\Delta\sigma$) is the is the spectrometer operational spectral range. For example, an arrayed MZI spectrometer operating over the 2.5 nm wavelength range at 0.1 nm resolution requires 50 MZIs. Since each MZI couples to a separate input waveguide, in this example the optical throughput is obviously increased by a factor of 50 compared to a single input device.

In addition to the *étendue* benefit, an important advantage of this device is that deviations from the ideal design appear as systematic errors in the interferograms. Once the waveguide device has been fabricated and characterized, the errors can simply be corrected by a software calibration. This calibration ability is an important advantage of our device compared to an AWG. In the AWGs there is no direct physical access to the arrayed waveguide output aperture, which makes measuring and correcting phase errors of an AWG a formidable task. Unlike in an AWG, our device provides physical access to each of the arrayed interferometer outputs where both phase and amplitude errors can be readily measured as part of the spectrometer calibration procedure.

The arrayed MZI spectrometer was simulated for the silicon-on-insulator (SOI) waveguide platform for the application in spatial heterodyne observations of water (SHOW). The SHOW experiment includes detection of water absorption bands on the solar irradiance background in the 2.5 nm wavelength range centered at 1364.5 nm, with spectral resolution 0.1 nm. We choose an SOI with a comparatively thick Si layer (4 μm) to maximize the aperture size of the individual waveguides. According to vectorial mode solver calculations, the etch depth of 2.3 μm and the ridge width of 2.6 μm give a singlemode waveguide with the effective index n_{eff} = 3.4977, where the TE- and TM-like polarization modes are degenerate, as required for polarization insensitive operation. According to Eqs. 2 and 3, for the wavelength resolution of $\delta\lambda$ = 0.1 nm, an array comprising 50 MZIs with the maximum delay ΔL_{max} = 5.32 mm is required. By comparing the ideal water absorption spectrum (Fig. 2, curve a) and the retrieved spectrum (Fig. 2, curve b), it is observed that spectral features finer than the Rayleigh resolution limit (0.1 nm) are not yet resolved. These spectral features can be retrieved by improving the spectrometer resolution from 0.1 nm to 0.025 nm. This is done by increasing the maximum delay from 5.32 mm to 21 mm and using 200 MZI structures instead of 50. The spectrum retrieved by such a device is shown in Fig. 2, curve e. It is also noticed that the optical throughput of such device is increased by a factor of 200 compared to a single aperture device.

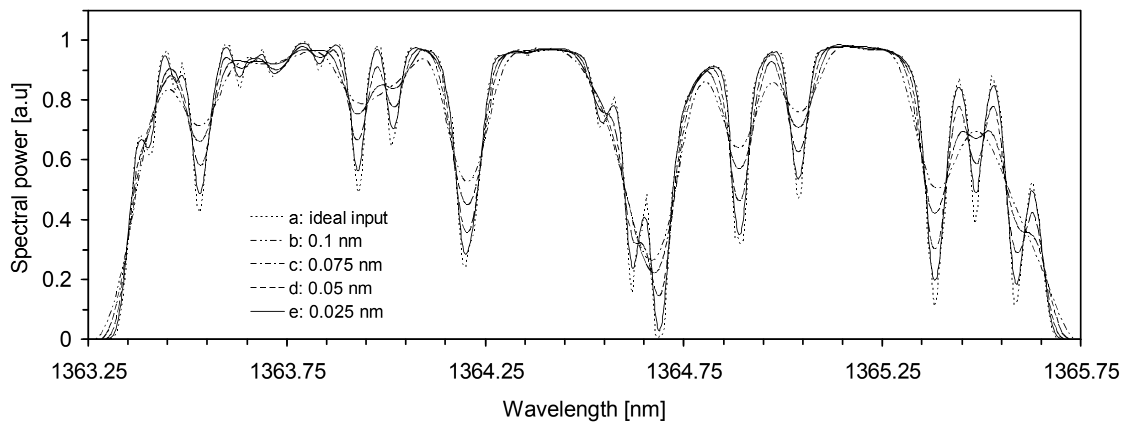

Fig. 2. Ideal input (curve a) and calculated spectra for the arrayed MZI spectrometer with the wavelength resolution of 0.1 nm (b), 0.075 nm (c), 0.05 nm (d), and 0.025 nm (e).

Conclusions

We have discussed a new waveguide spectrometer concept, namely multiaperture Mach-Zehnder interferometer array. Its advantages include a large optical throughput and a static (no moving parts) design. These are important benefits in applications where size and weight are critical. Fabrication robustness is another obvious advantage of this device. Phase and amplitude errors can be readily measured and corrected by calibration software with no need for costly modification of the waveguide physical properties by microfabrication tools.

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