Novel Concept for a Broadband Co-propagative Stationary Fourier Transform Spectrometer Integrated on a Si_3N_4 Waveguide Platform

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Abstract: We present a novel concept for a stationary Fourier transform spectrometer integrated on a Si_3N_4 waveguide platform. This spectrometer can reach high resolution ($\sim$1 nm) over a broad spectral band ($\sim$100 nm) within an area of 0.1 mm^2.

OCIS codes: (130.3120) Integrated optics devices, (300.6190) Spectrometers.

1. Introduction

For a long time, spectrometers have been important devices in various fields, including astronomical radiation analysis, biochemical sensing and food quality control, to name a few. Nowadays, we all witness an ongoing trend towards the miniaturization and integration of these instruments to enable portable and robust devices. Additionally, modern spectrometers still pursue broadband operation in combination with high resolution. Both can be achieved with Fourier transform infrared spectrometers (FTIR or FTS).

There are mainly two types of integrated FTS: the stationary wave integrated FTS (SWIFTs) [1] and the spatial heterodyne spectrometer (SHS) [2]. Although the interferogram is generated in different ways, both types of FTS require a detector array to record the interferogram. In a SHS, increasing the bandwidth for a given spectral resolution means a larger number of Mach-Zehnder interferometers [2], indicating a rapidly increasing size of the device. The underlying principle allows SWIFTs to have high resolution with a small size. However, the operational bandwidth is limited for a given detector array pitch. In both the Lippmann and the counterpropagative configuration [1], the period of the interferogram, $\lambda/(2n_{eff})$, is much smaller than the pixel pitch of commercially available detector arrays. Consequently, the interferogram is subsampled which restricts the operational wavelength range. To overcome this bandwidth restriction and to obtain high resolution within a small area, we propose a novel way to implement an integrated FTS. The device can be integrated on a Si_3N_4 or *SOI* photonic waveguide platform for cost-effective mass fabrication [3,4].

2. Co-propagative stationary FTS concept

In the proposed co-propagative stationary FTS, we first split the signal to be spectrally analyzed into two parallel single mode waveguides with a different width. Due to a proper spacing of the parallel waveguides, the evanescent fields of the two excited waveguide modes slightly overlap. As both modes propagate at a slightly different phase velocity, their evanescent tails will beat with each other and generate an interference pattern in between the two waveguides. By placing a fine grating in between both waveguides, this interference pattern can be diffracted upwards to a photodiode array. A schematic of the FTS layout is shown in fig.1A. We use a 3dB multimode interference coupler (MMI) to split the signal. If we consider two waveguide modes with propagation constant β_1 and β_2, the spatial beatnotes in the interferogram will vary as $\cos(\Delta\beta z)$, with z the propagation distance and $\Delta\beta = \beta_1 - \beta_2 = 2\pi\Delta n_{eff}/\lambda$, where λ is the operation wavelength and Δn_{eff} is the difference in effective index of the two waveguide modes. Therefore, compared with SWIFTs, we actually increase the period of the interferogram by a factor of $2n_{eff}/\Delta n_{eff}$, making it easier to sample it with commercially available photodiode arrays.

2.1. Bandwidth and resolution

The Nyquist-Shannon sampling theorem tells us that, in order to avoid subsampling, the pixel pitch of the photodiode array should be less than half of the smallest period of the beatnotes, $\Lambda < \lambda_{min}/(2\Delta n_{eff})$. So, for a give pixel pitch, the operational bandwidth only has a lower limit of $2\Lambda\Delta n_{eff}$. On the other hand, the limited interferogram length L

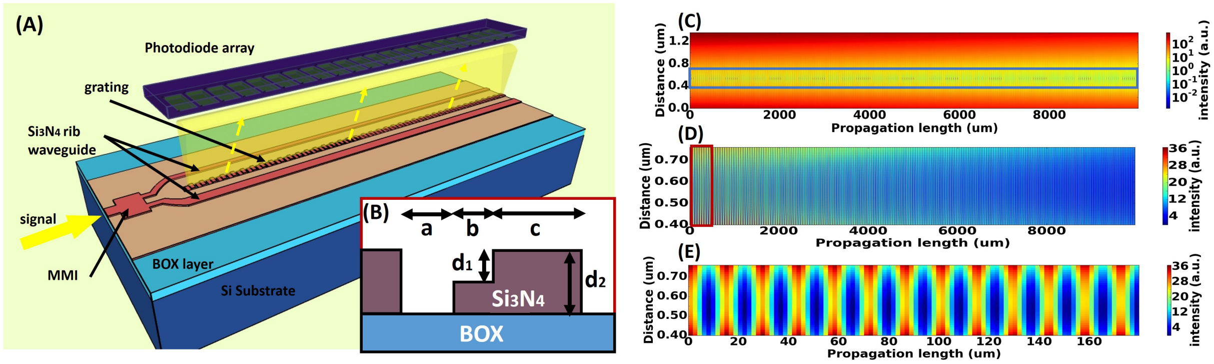

Fig. 1: (A) Conceptual drawing of the co-propagative stationary FTS. (B) Side view of one grating element. (C) Interference pattern between the two waveguides where the blue frame marks the position where the grating is located. (D) The interferogram in the grating region. (E) A zoom-in of the first several periods.

leads to spectral broadening in Fourier domain, where a delta-function becomes a $sinc-$function $\sin(\pi f_z L)/(\pi f_z L)$ with f_z the spatial frequency which in our case equals $\Delta n_{eff}/\lambda$. The FWHM of such a $sinc-$function is given by $1.207\lambda^2/(\Delta n_{eff} L)$. This is also the expression of the attainable spectral resolution.

2.2. Design of the grating

The grating is a key component of this FTS design. It should have strong directionality, i.e. diffract most of the optical power upwards. Moreover, the design of the grating should ensure very weak reflection and minimizes the contradirectional coupling between the two waveguides. The grating strength imposes an optimal gap between both waveguides. For optimal SNR, we want the optical power in the waveguide to decay 1/e over the device length, which equals the length of the interferogram and could be in the order of one centimeter. Furthermore, the position of the grating is critical for the contrast of the beating pattern. Preferably, we want the evanescent field of the two waveguide modes to be of similar strength in the region where we put the grating. Under all these considerations, we choose an asymmetric grating, shown in fig.1B. Taking into account a minimum feature size of 150 nm (to be compatible with the processing of Si_3N_4 waveguides in a CMOS line), a directionality of about 0.9 can be obtained around a wavelength of 850 nm with a=180 nm, b=160 nm, c=280 nm d_1=150nm and d_2=300nm.

2.3. Spectrometer implementation around 850 nm

Let us consider a center wavelength of 850 nm and a spectral bandwidth of 100 nm for the spectrometer. At the minimum wavelength of 800 nm, using Si_3N_4 rib waveguides (thickness of 300 nm, shallow etch of 150 nm, top oxide) with a width of 300 and 800 nm respectively, yields an effective index difference of 0.056 between the TE guided modes of both waveguides. Given a propagation length of 1 cm, the theoretical spectral resolution is then calculated to be 1.38 nm. In fig.1C, we show simulation results of the interferogram between two waveguides spaced by 1.36 μm, the period of interference pattern is calculated to be 14.28 μm as one can also see in fig.1E. This requires a photodiode array with Λ less than 7.14 μm, which is commercially available. In this scenario, the size of our device is only about 0.1 mm^2 (width$\sim$0.01 mm and length=10 mm).

3. Conclusion

We report a novel way to implement an integrated stationary FTS. While the concept has been elaborated for the Si_3N_4 waveguide platform, it can readily be extended to the *SOI* waveguide platform to address different wavelength ranges. From simulation, we prove that this design has excellent spectral resolution together with the capability of broadband operation. The small size and expected low insertion loss make this spectrometer suitable for further integration into various lab-on-a-chip systems, such as on-chip Raman and absorption spectroscopic systems.

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