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On-chip silicon nitride optical phased array as a broadband near-infrared spectrometer

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ABSTRACT

We demonstrate a novel spectrometer based on a hybrid guided wave and free-space optical system, consisting of a silicon nitride optical phased array (OPA), free-space grating couplers, and Fourier-space imaging to an image sensor. Each wavelength dispersed by the photonic integrated circuit corresponds to a unique position in the Fourier plane. We demonstrate the reconstruction of a spectrum in the near-infrared from the position and the intensity in this plane. From preliminary measurements on a small-sized OPA (0.1 mm^2), we report a spectral range of 100 nm and a resolution of around 0.5 nm.

Keywords: Integrated spectrometer, optical phased array, silicon nitride

1. INTRODUCTION

Optical spectrometers are essential in various fields, including biomedical sensing and chemical analysis. With the development of sensors based on photonic integrated circuits, there is a growing need for integrated spectrometers with broad spectral range, good resolution, and sufficient sensitivity.

In this work, we present a novel broadband silicon nitride spectrometer based on an optical phased array (OPA). The OPA consists of arrayed waveguides with a fixed delay length difference and grating couplers for off-chip coupling.[1] Each wavelength dispersed by the OPA corresponds to a unique direction characterized by angles θ_x and θ_y from the normal of the sample surface. With the Fourier-space imaging technique, each direction corresponds to a point with a unique coordinate $(\sin\theta_x, \sin\theta_y)$ in the back focal plane of a microscope objective. Previously, the component is developed as a beam steering component on SOI platforms.[1] It can also replace the dispersive component in conventional spectrometers. A spectrum of the input signal can be reconstructed after capturing the intensity and positions of the diffracted fields with a camera. We develop such a spectrometer on a silicon nitride platform for sensing applications in near-infrared range.[2] With this novel configuration of a hybrid guided wave and free-space optical system, we can realize good sensitivity, resolution, and spectral range using a compact system.

2. DESIGN AND FABRICATION

The OPA shown in Figure 1 is fabricated on a silicon nitride (Si_3N_4) platform. The 300 nm thick Si_3N_4 is deposited via plasma-enhanced chemical vapor deposition by IMEC. The waveguide trenches and grating couplers are defined using electron beam lithography and reactive ion etching, with an etch depth of 300 nm. Light is coupled from free space to the photonic waveguide through an objective and an edge coupler. A free-space polarizing beam splitter is installed before the objective to ensure only the quasi-TE mode is excited in the waveguide. The edge coupler is tapered to an 800 nm-wide waveguide, the input waveguide in Figure 1. Light is split through the star coupler to 32 waveguides, which are also 800 nm wide. The waveguides have ascending lengths, with a fixed difference of 24.9 μm, forming an arrayed waveguide grating (AWG). At the end of each waveguide, a grating coupler is etched to diffract light out of the sample plane. The grating pitch is 500 nm, and the fill factor is 0.5. The center-to-center distance between each grating coupler is 1.6 μm.

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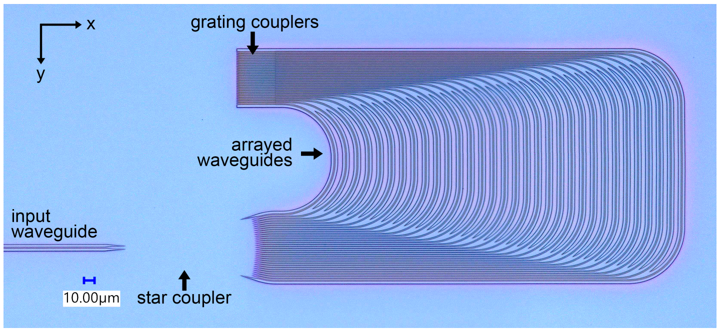


Figure 1. Two-dimensional OPA fabricated on a Si_3N_4 platform, observed under an optical microscope.

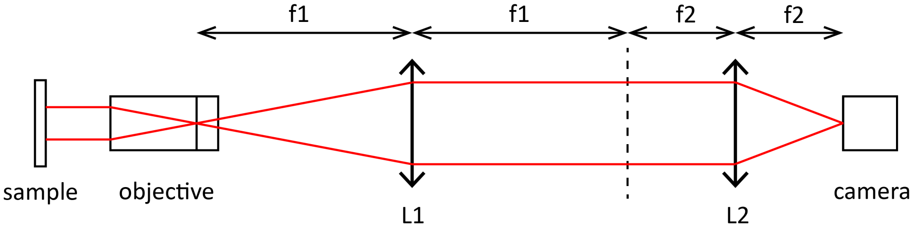


Figure 2. A sketch of the Fourier-space imaging setup

The grating couplers not only couple light out-of-plane but also steer the light slowly in the x-direction when tuning wavelength. The steering angle θ_x relative to the sample normal is governed by the phase matching condition at the grating, involving wavelength, grating pitch, grating effective index, and cladding index. Meanwhile, light is also steered more rapidly in the y-direction with an angle θ_y due to the phase difference between each waveguide in the AWG. The two steering mechanisms form a two-dimensional OPA as described by Van Acoleyen et al.[1] With this component, each wavelength is dispersed to a unique direction characterized by (θ_x, θ_y).

With the Fourier-space imaging technique,[3] light with the direction of (θ_x, θ_y) is imaged onto the far-field as a spot with a coordinate of $(\sin\theta_x, \sin\theta_y)$. The output first passes through a microscope objective, of which the numerical aperture (NA) limits the maximum observable angle. The far field is imaged in the back focal plane of the objective, which is then imaged onto an image sensor, as shown in Figure 2. We use a lens with f_1 =200 mm and another lens with f_2 =100 mm. The transverse magnification is 0.5. Figure 3 shows the far-field pattern of different wavelengths captured with the image sensor. The spot width in the x-direction depends on the out-coupling strength of the grating coupler, while that in the y-direction depends on the total number of waveguides and the spacing between grating couplers. When the correspondence between wavelength and far-field coordinates and between input and output intensities is known, a spectrum of the input signal can be reconstructed from the far field.

3. MEASUREMENT RESULTS

Firstly, the OPA is tested using a tunable laser ranging from 750 nm to 850 nm. We record the wavelength, input power, position on the far field, and intensity on the image sensor while tuning the laser with a step size of 1 nm. Figure 4 shows the far-field position of the output beam in x- and y-directions in pixel numbers. The average steering speed in the y-direction is 81.4 pixel/nm, while the average full width at half maximum (FWHM) in the y-direction is 44.1 pixels. Hence the spectral resolution is around 0.5 nm. The square pixels are 4.65 μm wide. The resolution can be improved by adding more waveguides to the array to reduce the spot size or increasing the delay length to steer faster. Besides the on-chip footprint, the resolution is also limited by the pixel size of the camera and the magnification factor of the imaging system. Note that the intensity of two adjacent spots may differ significantly, where the resolution may be slightly worse than the one defined by FWHM.

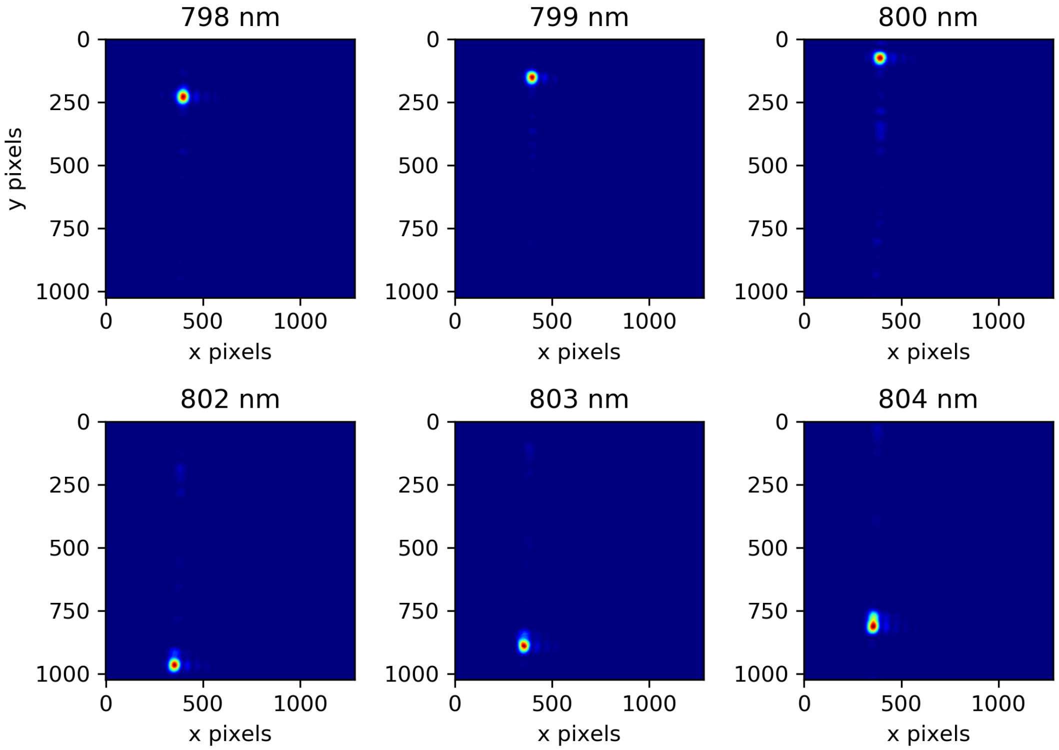


Figure 3. Far-field pattern of the OPA of different wavelengths, captured with an image sensor. Pseudo-colored to show intensity.

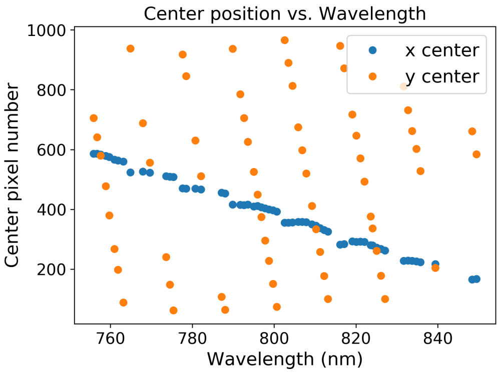
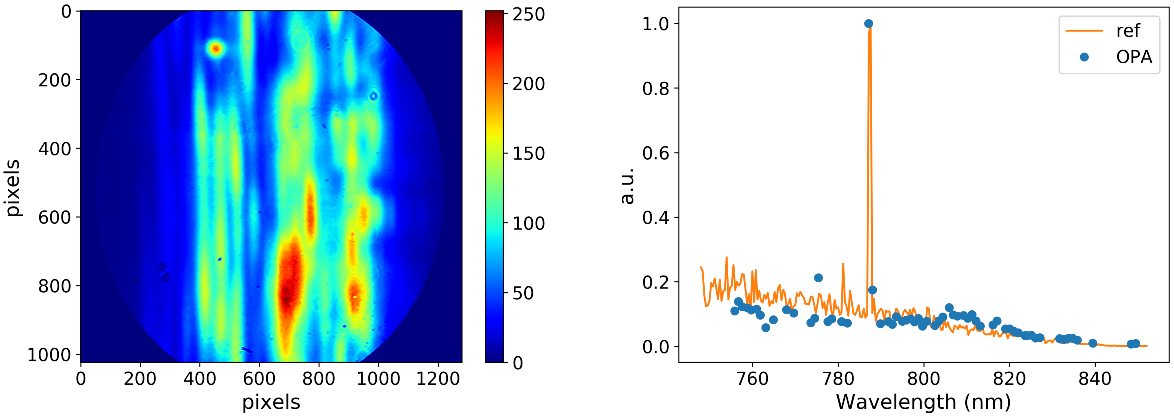


Figure 4. Far-field pattern of the OPA of different wavelengths, captured with an image sensor.

Periodically, a new order of the AWG moves into the field of view (FOV), while the previous one moves out. When two spots of different orders share the same y-position, sufficient separation in the x-direction prevents overlapping. In theory, the spectral range of this spectrometer is determined by the transmission of the grating couplers and the NA of the objective, which can easily cover 200 nm. In practice, it is also limited by the spectral range of the tunable laser used during the first test.

It may be noticed that the x-positions do not change smoothly with the wavelength. There are abrupt changes at wavelengths where the next order appears in the y-direction. It resulted from a rotated sample, as the x-axis on the sample does not align with the horizontal edge of the FOV. As long as the coordinates of all wavelengths are recorded, such rotation does not affect spectrum reconstruction.



(a) Far-field

(b) Reconstructed and reference spectra

Figure 5. Measurement of a broadband input signal. (a) Far-field pattern of the OPA. Pseudo-colored to show intensity. (b) Spectrum reconstructed from the far-field (blue dots). The spectrum measured with an optical spectrum analyzer (orange line) is included as reference.

Then, we replace the input with a broadband test signal. The corresponding far-field is shown in Figure 5(a). The FOV is limited by the pupil of the objective. From the first test, we obtain the relations between wavelength and far-field position and between input and output intensities. With these relations, we can reconstruct a spectrum from the far field. The result is shown in Figure 5(b) in blue dots. The same signal is also measured by an optical spectral analyzer, which is included in Figure 5(b) for comparison. We observe good agreement in wavelength and relative intensity. The slight difference in relative intensity can be improved by increasing the signal intensity and more careful calibration of input and output intensities.

4. CONCLUSIONS

We have demonstrated a broadband near-infrared spectrometer based on an on-chip Si_3N_4 optical phased array (OPA). The OPA consists of an input waveguide, a star coupler, and 32 arrayed waveguides with grating couplers. Based on this two-dimensional OPA, each wavelength is emitted in a unique direction characterized by two angles (θ_x, θ_y) relative to the surface normal. With the Fourier-space imaging technique, each direction corresponds to a spot on the far field with a coordinate of $(\sin\theta_x, \sin\theta_y)$. It is imaged onto an image sensor through a microscope objective and a two-lens system. If the relations between wavelength and far-field coordinates, and input and output intensities are known, a spectrum of the input signal can be reconstructed from the far field. The spectral resolution depends on the steering speed and spot size, while the bandwidth is limited by the grating couplers and NA of the microscope objective. With a compact size of 0.5 mm×0.2 mm on chip, the resolution is measured as 0.5 nm. We demonstrate the reconstruction of a broadband spectrum in the spectral range of 750 nm–850 nm. A good resolution is realized in a broad spectral range with a small footprint on-chip.

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