Serpentine Integrated Grating Spectrometer

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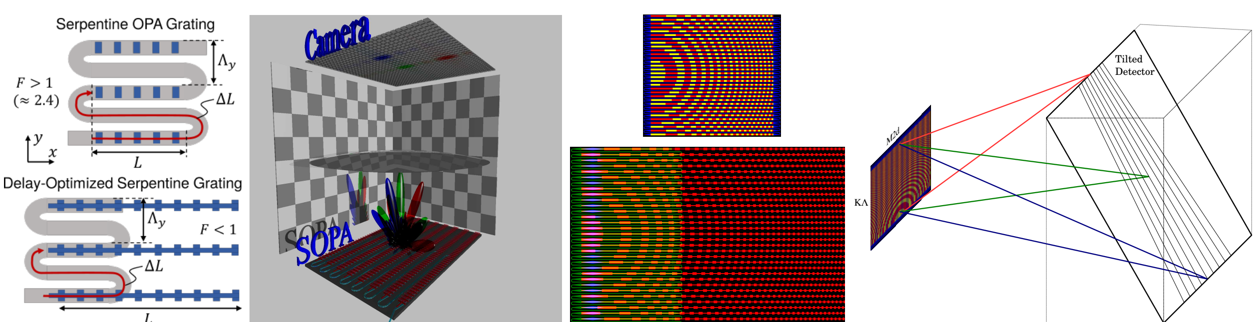
Abstract: The serpentine integrated grating spectrometer uses a meandering delay line and outcoupling grating rows to implement a crossed-dispersion wide-bandwidth integrated spectrometer with resolving power of 10^5 and 10^4 spectral bins in a few cm^3 volume.

The serpentine integrated grating (SIG) spectrometer is a new hybrid integrated-optic/free-space crossed-dispersion spectrometer design incorporating large differential time delay and crossed-dispersion in order to separate the spectrum in a 2-D raster. The SIG incorporates an area efficient long serpentine delay line, folding several centimeters of linear dimension into less than a square millimeter silicon photonic chip footprint. Free-space grating couplers directly imprinted on the rows of the serpentine delay line dispersively couple light out of the plane of the chip. The SIG architecture produces a 2-D coarse/fine wavelength-beamsteered emission pattern that is focused with a high NA achromatic Fourier transforming lens onto a SWIR focal plane array. We present an initial experimental demonstration of the SIG spectrometer utilizing our serpentine optical phased array (SOPA) designed previously for 2-D wavelength controlled lidar beamsteering [1] with a bulk optic lens while an improved design will incorporate focusing power directly into the SIG aperture [Fig. 1].

Spectrometer readout can either de-raster the 2-D data or project onto a measured spatial emission pattern with pre-recorded calibration data. To demonstrate this we recorded a calibration image of the array emission at 1 GHz steps across the entire 14 THz spectrometer bandwidth. At each frequency, the 2-D detector array response is measured and used to construct a calibration matrix which maps the input spectrum to a detected image. For each spectral image measurement, a central portion of the image wider than the grating lobe separation (640 x 201 pixels) is vectorized ($\vec{x}$ with 128,640 elements) and concatenated to the previous vectors to generate a matrix (128,640 x 14,254 elements) mapping each calibration frequency to a vector of pixel intensities. The resulting matrix $\overline{\overline{M}}$ maps a vector representing an input spectrum to a vectorized image corresponding to that spectrum through a non-negative least-squares matrix-inversion process. Operating bandwidth is demonstrated using a composite test image consisting of 28 equispaced lines from 1540 to 1650 nm. We demonstrated resolving power of over 120,000 by simultaneously coupling in a second laser emitting at a stable single frequency and sweeping the first laser past this stable line to measure 1.6 GHz resolution at 1550 nm.

To further simplify the optics of the SIG spectrometer, a grating with focusing power based on an incorporated quadratic phase factor (QPF) in the out-coupling waveguide can be used to eliminate the required



a) b) c) d)

Figure 1: a) Serpentine Optical Phased Array (SOPA) for lidar beamsteeering and Serpentine Integrated Grating (SIG) device topologies, b) Emission from the serpentine integrated grating aperture is focused onto a detector array with an achromatic Fourier transforming lens. c) Alternative design integrates the focusing power of the lens directly into the aperture. Schematic representation of a focusing SOPA (top) and SIG (bottom) out-coupling grating with linear variation of the grating frequency along each row. The starting phase of each row varies quadratically from row to row up to the Nyquist limit and with equal focusing power along the two axes. d) Operation of the free-space focusing output at three wavelengths with a focal distance proportional to the optical frequency is accommodated for by appropriately tilting the 2-D detector array.

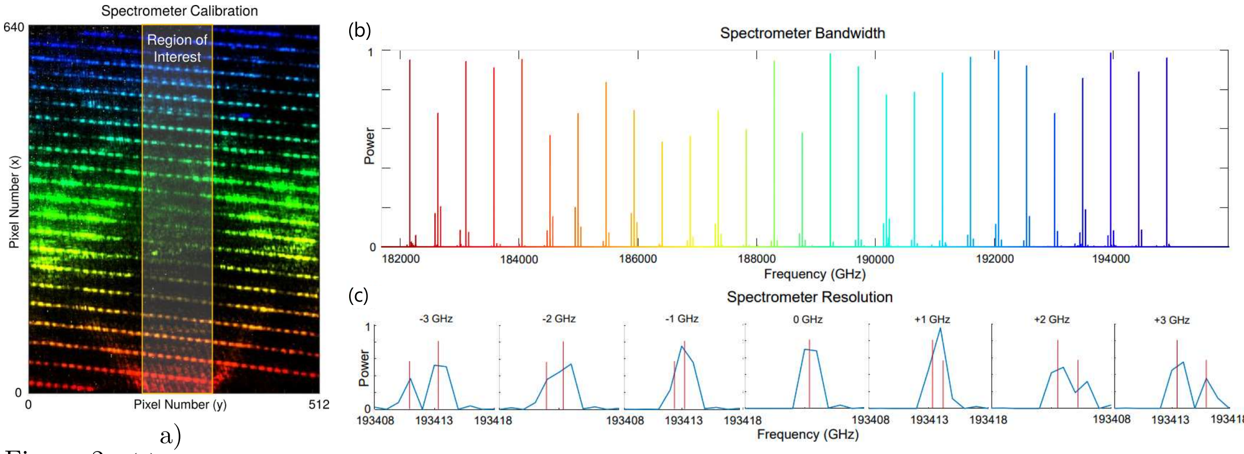


Figure 2: (a) False-color coded 2-D cross-dispersed detector plane output at 50GHz intervals across the bandwidth from 1530-1650 nm that fits on the 640×512 SWIR detector array with an F=23mm lens. (b) Spectral reconstruction of 28 distinct single-frequency inputs covering a 1540 nm to 1650 nm spectrometer bandwidth. (c) Calibration output (blue) for two nearby laser lines (ground-truth frequencies red) as one laser is stepped by 1 GHz increments, demonstrating spectral resolution of ~ 1.6 GHz.

achromatic large NA low-aberration lens as shown in [Fig. 1]. The high-resolution micro spectrometer can then be implemented with a single focusing SIG and an appropriately tilted 2-D detector array with either free space or possibly liquid or solid immersion layer of index n_g. This further reduces the out-coupling angles and increases the achievable bandwidth and number of resolvable spots by about n_g.

Our presently demonstrated version of the SOPA spectrometer suffers from cross talk along the coarse frequency axis caused by excess delay accumulation $F = \frac{T_{serpentine}}{T_{grating}} > 1$ in the flyback waveguides, manifesting as unacceptably large crosstalk side lobes at multiples of the 40 GHz FSR seen in [Fig. 2(b)]. Our presently fabricated devices have a greater row-to-row delay time than the time delay across each grating coupler, resulting in inadequate separation along the coarse frequency axis. A refined design places the grating coupler waveguides on a separate device layer above the serpentine delay line layer, allowing for both delay optimization $F < 1$ [Fig. 1(a)] and more optimal power extraction by using, for example, nitride overbar free-space grating couplers instead of the weakly radiating sidewall gratings utilized in this first demonstration. Further, by optimizing the coupling between the serpentine delay line and each grating row we can assemble a SIG with more rows and higher outcoupling efficiency within each row, providing both higher resolution and substantially lower system insertion loss.

We have completed an initial demonstration of a novel serpentine integrated grating spectrometer. The serpentine integrated grating spectrometer achieves high resolution, large bandwidth, and small system volume, simultaneously exceeding alternative integrated optic spectrometers along all 3 performance axis [2, 3]. The hybrid integrated-optic/free space architecture allows for drastically improved resolving power and number of spectral bins as compared to existing fully integrated spectrometer technologies and dramatic reduction of system volume while maintaining comparable resolving power to fully free-space crossed dispersion approaches employing VIPAs or echelles in combination with gratings or prisms [4]. Next generation QPF focusing gratings employing the SIG row architecture with more lower index rows will further increase the resolving power, bandwidth, and number of resolvable spots.

References

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