Simultaneous High-Resolution and High-Throughput Spectrometer Design Based on Virtual Slit Technology

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Abstract: The classic trade-off between resolution and throughput in a dispersive spectrometer is eliminated using virtual slit technology. An optimized spectrometer incorporating a virtual slit designed from the ground up is experimentally demonstrated.

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OCIS codes: 120.6200, 300.6320

1. Introduction

The use of slits has a long and rich history in optics serving many purposes, but perhaps the most well known application of a slit is to improve the spectral resolution in a dispersive spectrometer. William Wollaston was the first to use a slit in a dispersive spectrometer in 1802, and they have been used extensively ever since [1]. However, a serious limitation of the slit aperture at a conjugate focal point is that it rejects a large fraction of the incoming light, resulting in the well known classic trade-off between spectral resolution and optical throughput in dispersive spectrometers.

Several technologies and techniques have tried to overcome the use of a slit and still achieve high spectral resolution with maximal throughput—these are most commonly known as optical slicers. The first optical slicer was invented by Bowen in 1938 to be included on an astronomical spectrometer [2]. The Bowen slicer used plane mirrors to divide a round stellar image into narrow strips. The device was large, bulky, and awkward to use, but it did achieve some success. Some years later in 1972 the Bowen slicer was modified by Walraven and Walraven and was called the Bowen-Walraven slicer [3]. The Bowen-Walraven slicer still operated on the same principle as its predecessor, but used total internal reflection inside a solid prism instead of reflective plane mirrors. While the Bowen-Walraven slicer was robust, its performance was limited—the slices were not optimally aligned along the cross-dispersion axis and the high dispersion of the glass make it unsuitable for specific interferometric applications.

More recently the concept of slicing has been extended to a waveguide approach using optical fibers or thin glass slides [4, 5]. Fiber optic “spot-to-line” converters make use of a bundle of fibers to convert a large mostly uniform (often circular) collection area at the entrance to a tall and narrow emission at the exit. While multi-fiber based spectrometers boast an increase in collection efficiency, the fiber approach to slicer-based spectrometer design has inherent limitations. First, the total collection area compared to the light sensitive collection area will never be ideal since each fiber must have some amount of cladding material around its core. Second, the light collection solid angle cone is fixed and limited as dictated by the fiber material—slow beams often suffer from focal ratio degradation within the fiber, wasting etendue. Third, the light is forced to travel long distances through the dispersive material of the fiber. Fourth, the spectral resolution will still be limited by the diameter of the individual fibers unless a slit is used, so the classic trade-off between resolution and throughput has not been fully overcome.

2. HTVS™ Concept and the Optical Pupil Slicer

The aforementioned technologies and techniques of optical slicers can all be categorized as image slicers, meaning that they attempt to divide up the image, or focused spot, and rearrange the light to produce a narrower point spread function along the dispersion axis resulting in higher spectral resolution in a dispersive spectrometer. An alternate way to achieve a narrowing of the point spread function while preserving light throughput is to manipulate the light field distribution in collimated space, or pupil space. Such a device is called an optical pupil slicer, and its resulting effect
Fig. 1. (a) Vertically binned spot profiles of a 50 µm fiber input with a 5:1 imaging magnification. The blue plot shows the fiber image with no slit, the red plot shows the fiber image with a 15 µm slit, and the green plot shows the fiber image after passing through the HTVS only. (b) Raman spectrum of turpentine captured using a 532 nm Raman probe system with a 30 mW laser. The blue plot shows the result from OEM spectrometer A, the red plot shows the results from OEM spectrometer B, and the green plot shows the results from the Sensei-532 spectrometer.

is to produce a virtual slit. Based fundamentally on the radiometric principle of étendue and the optical Fourier shift theorem, a pupil slicer may be realized using a relatively few number of simple optical components. Simply stated, the étendue is a 2D geometrical measurement of the light collected in an optical system given a finite source area and a finite entrance pupil area. Mathematically this may be represented as \( \Xi = A_s \Omega_{EP} \), where \( A_s \) is the area of the light source and \( \Omega_{EP} \) is the solid angle of the entrance pupil as seen by the source \(^1\) [6].

Because the étendue only depends on the area of the source and the 2D description of the pupil shape, i.e. the solid angle, the sub-geometrical description of the area and solid angle may be arbitrarily defined as long as the product remains constant. For example, if the width of a source area is decreased by a given factor, \( S \), while the height of the source is increased by the same factor, \( S \), the total area has not changed, and therefore the solid angle, and hence the étendue and throughput, will be the same. By decreasing the source width along the dispersive axis of the spectrometer the spectral resolution is increased, but increasing the source height along the cross-dispersive axis does not affect the resolution.

The first published results from a refractive based optical pupil slicer showed that the resolving power of a dispersive spectrograph could be increased by 2X with an 85% throughput efficiency [7]. A purely reflective based optical pupil slicer has since been developed as a commercial product by Tornado Medical Systems, called the High Throughput Virtual Slit™ (HTVS) [8]. This HTVS configuration provides a 4X improvement in the spectral resolution with a 94% throughput, and does not suffer from chromatic aberrations due to the reflective design. The HTVS device is a component that easily inserts into the collimated beam within pre-existing spectrometers. It serves as a black box device that maintains the same f/#, of the spectrometer, but offers a 4X improvement in spectral resolution with virtually no throughput loss. A visual representation of the HTVS concept can be seen in Fig.1(a).

3. The Sensei™ Spectrometer

The advantages provided by a virtual slit can be enhanced by designing the full spectrometer around the virtual slit concept, rather than inserting an HTVS module into a pre-existing spectrometer. Arjae Spectral’s Sensei™ spectrometer is the first commercially available spectrometer which incorporates a virtual slit as an integral part of its design. Because of this holistic approach to the design, many redundant components can be eliminated, making the Sensei more compact, manufacturable, and robust than a traditional spectrometer with an HTVS inserted. This approach brings all the advantages of a HTVS to the end user while eliminating any concerns about proper integration and alignment.

\(^1\)This formulation is only valid in the small angle paraxial approximation.
The spectrometer takes a 200 µm core multi-mode fiber input of 0.22 NA and collimates the light. Next the light is passed through a virtual slit with a throughput of 95%. Upon passing through the virtual slit the light transmits through a volume phase holographic grating and finally focuses onto a detector with a complex camera lens.

The spectrometer uses all-reflective components except for the collimating lens, camera focusing lens, and a highly efficient volume phase holographic transmission grating, thus making it straightforward to adapt the design to different band-passes. Two configurations of the spectrometer have been demonstrated: a VIS version and a NIR version. The VIS version operates over the bandpass 480-680 nm, while the NIR version operates over the bandpass 670-1100 nm. The two spectrometers are well suited for Raman spectroscopy providing a peak throughput efficiency at 600 nm and 950 nm respectively. The spectral resolution of the two spectrometers are 0.24 nm and 0.5 nm respectively, using the entire output aperture of a 200 µm fiber. In order to achieve similar spectral resolution in a slit-based spectrometer design, slit widths of 10 µm would be required, blocking a large fraction of the light. Since Sensei uses the entire 200 µm fiber, the advantage over the classic design is a 15X realization in light throughput through the virtual slit.

3.1. Results

The VIS configuration of the spectrometer was used in a 532 nm Raman probing system and compared against two similarly classed slit-based spectrometers. The other two spectrometers (called OEM A and OEM B) were chosen based on their similar band-passes, resolution, size, cost, detector read noise and gain, and overall design as an OEM Raman spectrometer. OEM A contains a 25 µm slit and a corresponding 18 cm⁻¹ resolution, OEM B contains a 10 µm slit and a corresponding 5 cm⁻¹ resolution, while Sensei contains no slit (or rather, a 10 µm-wide virtual slit) and a corresponding resolution of 7 cm⁻¹. A Raman spectrum of turpentine using the three spectrometers can be seen in Fig.1(b). The higher throughput spectrometers have a higher fluorescent floor signal, however the Raman signal SNR above the fluorescent signature is higher for the Sensei due to its simultaneous high-throughput and high-resolution.

4. Future Directions and Applications

The demonstrated Sensei™ spectrometer designs are optimized for a single 200 µm optical fiber input, but the virtual slit concept can also be configured to use multiple fiber inputs in parallel, converting each fiber into a virtual slit while maintaining spatial separation between adjacent fibers. Since the virtual slit concept preserves the spatial distribution of light along the input aperture, an extended slit can be anamorphically reformatted in the same fashion as a single fiber or column of fibers, such that the apparent source width along the dispersion axis is reduced and the spectral resolution is improved. This capability is highly advantageous for simultaneous spectral measurements of different spectroscopy targets, or a combination of targets and calibration sources. With suitable internal optics and a large array detector, a Sensei spectrometer can provide high-resolution high-throughput spectral analysis of dozens of sources simultaneously. This multiplexing advantage can be applied to many different application areas, such as process monitoring, remote sensing, Raman spectroscopy for laboratory analysis, quality control, and contaminant detection.

References