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Fiber based Spectrometer; Design Study & Comparison with a Grating based Spectrometer

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ABSTRACT: This paper presents the design study, operational principle and mathematical model of a fiber optic based spectrometer (FOS). Such a spectrometer is highly desired by the ever-increasing applications of fiber optic sensors in compared to a grating based spectrometer, where high response frequency is required while advantages of high accuracy and large dynamic range must be maintained. The white light interferometry could provide a solution for high accuracy and large dynamic range measurement without ambiguity because of its absolute measurement nature. However the signal demodulation speed is limited due to the low spectrum acquisition rate of the existing spectrometers.

The new (FOS) utilizes time domain dispersion of the sampled incoming light by dispersive fiber rather than the spatial dispersion employed by traditional spectrometers. In addition the signal that represents the spectrum of the light is naturally a serial signal which can be detected by a single detector and recorded by a high speed data acquisition device. Theoretical study of the operation principle is made and a mathematical model for the spectrometer is developed based on beam mode profile technique.

KEYWORDS: Fiber optic based spectrometer (FOS), grating based spectrometer, CCD camera, Resolution.

I. INTRODUCTION

Spectrometers are widely used tools in chemical and biological sensing, material analysis, and light source characterization. Traditional spectrometers use a grating to disperse light, and the spectral resolution scales with the optical pathlength from the grating to the detectors, imposing a trade-off between device size and resolution. In recent years the development of "miniature" spectrometers has enabled a host of new applications due to their reduced cost and portability. However, they still rely on grating dispersion, thus the spectral resolution is lower than the large bench-top spectrometers. In order to develop a compact spectrometer without sacrificing resolution, a multimode fiber turned, where a long pathlength is easily achieved in a small footprint by coiling the fiber [1].

II. GRATING BASED SPECTROMETERS

During the past 15 years compact, low cost spectrometers have grown to a fairly large market size of hundreds of millions of dollars, with applications ranging from medical hemoglobin content analysis over accurate color determination of textiles to sorting of LEDs in large semiconductor manufacturing plants. The majority of these compact spectrometers have been based on the Crossed Czerny-Turner configuration with a reflective diffraction grating as the dispersive element separating the wavelength content onto a linear detector array. Any spectrometer consists of three basic optical components (collimating optics at the input, a diffraction grating and focusing optics that

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focus different wavelengths of the spectrum onto different pixels on the detector array). Both the Crossed Czerny-Turner (CCT) and the Transmission Grating based Spectrometer (TGS) include these three elements. For the TGS, we will consider two basic designs which have slightly different characteristics – the Lens-Grating-Lens (LGL) using two lenses and a grating, and the Mirror-Grating-Mirror (MGM) using two mirrors and a grating. Figure (1) shows the CCT, the LGL, and the MGM spectrometer lay-outs and schematic beam [2].

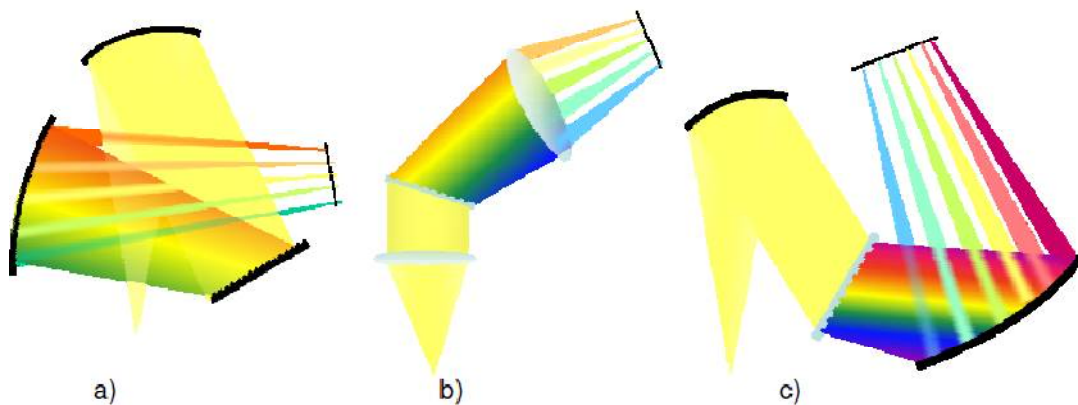


Figure (1): Spectrometer configurations: a) Crossed Czerny-Turner, b) Lens-Grating-Lens, c) Mirror-Grating-Mirror.

A spectrometer can in general not be optimized for all parameters, so it is important to compare only spectrometers that are designed for the same application.

2.1. Comparison of spectrometer configurations

A rough comparison of the characteristics in terms of resolution, throughput, and detector flexibility for the three spectrometer platforms provides in Table (1). As can be seen, all three platforms provide the same resolution relative to the wavelength range to be covered [3]. This is a consequence of the fact that the sizes of the beams relative to the optical components are roughly the same in all compact spectrometers and therefore the aberrations (determining the minimum resolution) are also roughly the same.

Table 1: Comparison of Czerny-Turner with the two transmission grating based Spectrometer configurations

Platform	Grating type	Minimum resolution (NA = 0.11)	Throughput λ_{st} to $2*\lambda_{st}$	Easy detector access
CCT	Reflective	~Range/700	~40 – 60%	No
LGL	Transmission	~Range/700	~60 – 90%	Yes
MGM	Transmission	~Range/700	~60 – 90%	No

In general, transmission grating based spectrometers (TGS) should be considered for spectroscopy applications and instruments where one or more requirements are important (Low light levels, Short integration time / fast spectral scans, Access to detector for OEM integration and High thermal stability). With recent developments in grating manufacturing, prices of transmission grating based and reflection grating based compact spectrometers are in the same range. So, the

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choice of spectrometer platform really has to be done based on technical requirements, so the optimum choice for your next spectroscopy platform might very well be a transmission grating based one.

III. FIBER OPTIC BASED SPECTROMETERS

The fiber-based spectrometer consists of a multimode fiber and a monochrome CCD camera that images the speckle pattern at the end of the fiber. The speckle pattern, created by interference among the guided modes in the fiber, is distinct for light at different wavelength, thus providing a fingerprint of the input wavelength. In this paper, a conventional multimode fiber can act as the dispersion element, enabling spectrometer operation using only a fiber and a camera. Interference enabling spectrometer operation using only a fiber and a camera. A multimode optical fiber is found as an ideal dispersive element for this type of spectrometer because the long propagation length and the minimal loss enable high spectral resolution and good sensitivity [4].

In a multimode fiber spectrometer, the interference between the guided modes creates a wavelength-dependent speckle pattern, providing the required spectral-to-spatial mapping. In the past, the contrast of this speckle pattern was found to depend on the spectral width and shape of the optical source [5], allowing researchers to use contrast as a measure of the laser linewidth. As opposed to using only the statistical property of the speckle such as the contrast, we recently proposed and demonstrated that by recording the entire speckle patterns at different wavelengths, a multimode fiber can be used as a general purpose spectrometer [6]. The spectral resolution of the device depends on the spectral correlation width of the speckle, which is known to scale inversely with the length of the fiber [7]. The advantage of using an optical fiber is that a long propagation length is easily achieved with minimal loss, giving high spectral resolution. Furthermore, the fiber-based spectrometer requires only a multimode fiber and a monochrome CCD camera to record the speckle patterns. Compared to traditional spectrometers, optical fibers are lower cost, lighter weight, and can be coiled into a small volume while providing spectral resolution that is competitive with state-of-the-art grating based spectrometers.

IV. MODELING AND DESIGN CONSIDERATION

We propose and demonstrate that a conventional multimode fiber can function as a high resolution, low loss spectrometer. The proposed spectrometer consists only of the fiber and a camera that images the speckle pattern generated by interference among the fiber modes. While this speckle pattern is detrimental to many applications, it encodes information about the spectral content of the input signal which can be recovered using calibration data. We achieve a spectral resolution of 0.15 nm over 25 nm bandwidth using 1 meter long fiber, and 0.03 nm resolutions over 5 nm bandwidth with a 5 meter fiber. The insertion loss is less than 10%, and the signal to noise ratio in the reconstructed spectra is over 1000. A schematic of the fiber spectrometer setup. A near-IR laser, wavelength tunable from 1435 nm to 1590 nm, will be used for calibration and testing. Emission from the laser is coupled via a single-mode polarization maintaining fiber (SMF) to the multimode fiber (MMF), with a standard FC/PC mating sleeve. A 50× objective lens is used to image the speckle pattern generated at the end facet of the fiber to the monochrome CCD camera [8], as shown in Figure (2-a). The speckle pattern as shown in Figure (2-b), which will be generated at the end of a 20 m multimode fiber as the input wavelength varies from 1500 nm to 1501 nm in the step of 0.01 nm. The wavelength is written on the top and also marked by the red line in the bottom scale. The speckle pattern decorrelates rapidly with wavelength, illustrating high spatial- spectral diversity gives fine spectral resolution.

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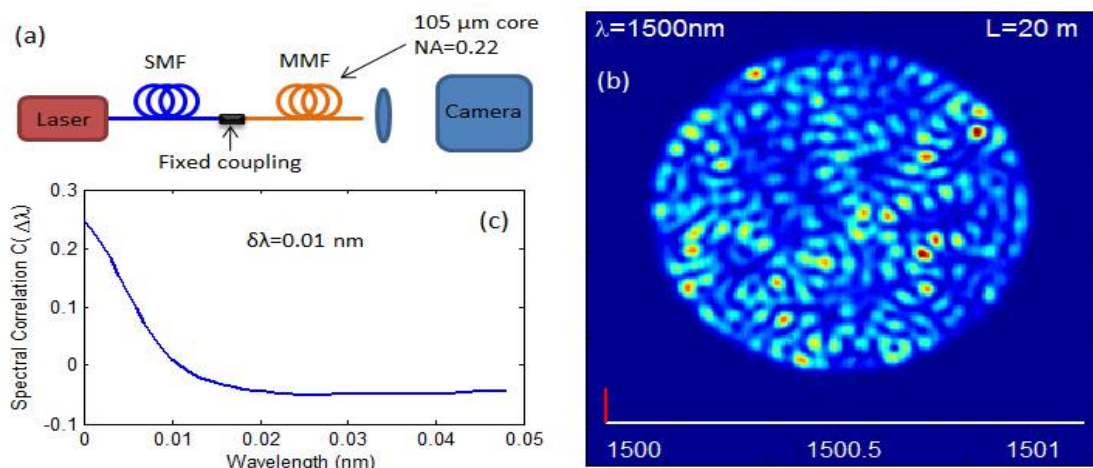


Figure (2): (a) Designed Setup,(b): Speckle pattern for expected results, (c):Spectral correlation function averaged over many spatial positions.

The spectral correlation function of the speckle intensity was calculated, $C(\Delta\lambda, x) = \langle I(\lambda, x)I(\lambda + \Delta\lambda, x) \rangle / [\langle I(\lambda, x) \rangle \langle I(\lambda + \Delta\lambda, x) \rangle] - 1 \dots\dots(1)$

Where $I(\lambda, x)$ is the intensity at a position x for input wavelength λ , $\langle \dots \rangle$ represents the average over λ .

In Figure (1-c), the spectral correlation function averaged over many spatial positions was plotted across the 105 μm core of a 20 m fiber. The spectral correlation width, $\delta\lambda$ is defined as: $C(\delta\lambda/2) = C(0)/2$. When the input wavelength shifts by $\delta\lambda$, the output speckle pattern becomes nearly uncorrelated, $C(\Delta\lambda = \delta\lambda) \approx 0$. In this case, $\delta\lambda = 10$ pm [9].

4.1. Advantages

1. Higher spectral resolution: Commercially available optical fiber are designed for long optical path lengths enabling very high spectral resolution (the proof-of-principle demonstration exhibited resolution of 0.03 nm at $\lambda=1500$ nm). Higher resolution can be achieved simply by using a longer fiber, allowing a fiber spectrometer to exhibit resolution equivalent to or better than the state of the art.
2. Smaller footprint: In traditional spectrometers, the resolution scales with the optical path length. To achieve resolutions less than 0.1 nm at $\lambda=1500$ nm, path lengths on the order of 100 mm are required and the total spectrometer footprint is typically ~1 meter. A Optical fiber can be coiled to achieve a similar path length with a much smaller footprint.
3. Lower-cost, lightweight all-fiber instrument: Traditional heavy, expensive spectrometer components and housing can be replaced with a single, low-cost multimode fiber.
4. Minimal insertion loss: The fiber spectrometer leverages the extremely low-loss of commercial optical fibers, enabling highly efficient spectrometer operation.
5. No special camera requirements: The simplest realization that can be introduced to the marketplace will be a multimode fiber and a camera operating in the wavelength region of interest.
6. Easily scaled to realize 2D imaging spectrometer for hyper spectral imaging: Appropriate commercially available imaging fiber bundles can be integrated with commercially available cameras for hyper spectral imaging. By using each core as its own spectrometer, a spectrally resolved image can be generated.

V. CONCLUSIONS

The main goal of this work was to study and understand the characteristics of fiber based spectrometer techniques. The conclusions can be summarized as show:

1. The fiber based spectrometer design study was demonstrated to analyze the multi-line or broadband spectrum of light sources up to 10 nm for different semiconductor laser diodes and LEDs.

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2. A high resolution, low loss spectrometer can be implemented in a multimode fiber with a 2D-CDD camera. Our approach is applicable to any wavelength range.
3. A low cost spectrometer that can be set up with modest effort and at low cost. It can be employed for general purpose VIS absorption, transmission, reflectance, and light emission and color measurements in several branches of the physical sciences and in chemistry and biology applications. Compared to existing spectrometers with comparable resolution and bandwidth, the multimode fiber spectrometer is compact, lightweight and inexpensive.

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