Evaluating Fiber-Based Spectrometers as a Key Component of Future Spectrometer Systems

Mustafa A. Al-Mansoori*[1], Dr. Khalid N. Al-Obaidi[2] & Leila S. Al-Rubai[3]
[*1,2&3]Center for Laser and Optoelectronics/ Directorate of Materials Research Ministry of Science and Technology/Baghdad-Iraq

ABSTRACT
A standard Multimode optical fiber can be used as a general purpose spectrometer after calibration the wavelength dependent speckle patterns produced by interference between the guided modes of the fiber. A theoretical analysis of the effects of the fiber geometry on the spectrometer performance, and then presents a reconstruction algorithm using a transmission matrix. Both fiber geometry and length have an effect on the spectral resolution and bandwidth, as well as the additional limitation on the bandwidth imposed by speckle patterns contrast reduction when measuring dense spectra is investigated. In a multimode fiber spectrometer, the interference between the guided modes creates a wavelength-dependent speckle patterns, providing the required spectral-to-spatial mapping. 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 and providing spectral resolution that is competitive with state-of-the-art grating based spectrometers.

KEYWORDS: Optical fiber, Spectrometer, Resolution, CCD camera.

I. INTRODUCTION

Traditional spectrometers operate by mapping input signals of different wavelength to different spatial locations. In most implementations, signals within a spectral band are mapped to a specific area where a detector is placed to measure its intensity. While such one-to-one spectral-spatial mapping is necessary for wavelength demultiplexer, it is not required for a spectrometer. In fact, spectrometers have been demonstrated which map a given spectral input to a complex spatial distribution of intensity [1]. As long as distinct spatial patterns are produced by light at different wavelengths, an arbitrary input spectrum may be recovered from the calibration data. This approach allows the grating in a traditional spectrometer to be replaced by almost any dispersion element, e.g., an array of Bragg fibers, a disordered photonic crystal lattice, or even a random medium [2]. These spectrometers, however, afford only modest spectral resolution, while suffering high insertion loss and/or low signal to noise ratio (SNR).

II. FIBER BASED SPECTROMETER SYSTEM

In this research, we demonstrate that 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. Interference of light propagating in multiple waveguide modes produces speckle, which varies with wavelength. Long propagation distance in the fiber leads to a rapid decorrelation of the speckle pattern with wavelength, giving high spatial-spectral diversity. After calibrating the speckle pattern as a function of wavelength, we reconstruct the spectra of input signals from the output speckles using a matrix pseudo-inversion algorithm in a combination with a nonlinear optimization procedure. We achieve a spectral resolution of 0.15 nm over 25 nm bandwidth using a 1 m long fiber, and 0.03nm resolution over 5 nm bandwidth with a 5 m fiber. The SNR is over 1000, and the insertion loss is less than 10%. Furthermore, the fiber can be coiled to provide a compact, light-weight, low-cost spectrometer, which could enable a host of new spectroscopic applications. Large core optical fibers can easily support hundreds of propagating modes, each having a different phase velocity. From a geometrical-optics point of view, various rays propagate down the fiber at different angles relative to the axis of the guide, thus they travel varying distances and experience different phase delays as they pass from the input to the output of the guide. While traditional spectrometers are based on one-to-one spectral-to-spatial mapping, spectrometers can also operate on more complex spectral-to-spatial mapping [3]. In these implementations, a transmission matrix is used to store the spatial intensity profile generated by different input wavelengths. A reconstruction algorithm allows an arbitrary input spectrum to be recovered from the measured spatial intensity distribution. While this approach is more complicated than the traditional grating or prism based spectrometers, it affords more flexibility in the choice of dispersive element. For instance, spectrometers based on this approach have been demonstrated using a disordered photonic crystal, a random scattering medium, and an array of Bragg fibers. We recently found that a multimode optical fiber is 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. 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. 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. In this paper, we extend on the proof-of-concept demonstration presented in Ref. [4] and explore the operational limits of a multimode fiber spectrometer. We provide a theoretical analysis of the effects of the fiber geometry on the spectrometer performance, and then present a reconstruction algorithm combining a truncated inversion technique with a least squares minimization procedure which enables accurate and robust spectral reconstruction in the presence of experimental noise. We also investigate the effects of, spectral and spatial oversampling on the quality of the recovered spectra. Using a 20 meter long fiber, we are able to resolve two laser lines separated by merely 8 pm. A higher spectral resolution is expected for a longer fiber, but we are currently limited by the resolution of the tunable laser source used for calibration. We also discuss the bandwidth limitation when measuring dense spectra due to speckle contrast reduction. To reduce the reconstruction error and increase the spectral bandwidth, we develop a method based on a polarization-resolved speckle measurement. Finally, we use a 2 centimeter long fiber to measure a continuous broadband spectrum generated by a supercontinuum source.

III. EXPERIMENTAL SETUP & MEASUREMENTS.

We propose and demonstrate that a conventional multimode fiber can function as a high resolution, low loss spectrometer. The proposed spectrometer consists only of a multimode optical fiber and a monochrome CCD camera that images the speckle pattern generated by interference among the guided modes in the fiber at the end of the fiber. The speckle pattern is distinct for light at different wavelength, thus providing a fingerprint of the input wavelength.

In our experiment we used commercially available step-index multimode silica core THORLABS fiber (FG105LCA) with NA=0.22, the core diameter of 62 µm, and the cladding diameter of 125 µm and the lengths varying from (1m, 5m to 10m) . a (633 nm) wavelength Laser diode (LD) that consumes power of (1mW) and a bench top 5mW laser diode of 630nm source are used to provide a spectrally controlled input signal for the calibration and initial characterization. A single mode optical fiber is used to couple the laser emission into the multimode fiber through a standard FC/PC mating sleeve this ensures that the input to the multimode fiber will have the same spatial profile as the calibration. The speckle pattern generated at the exit face was imaged onto an Beamage imaging system (genetic) which consists of the (interchangeable) camera (Charge-Coupled Devices CCD) head, 2m long USB cable is directly connected with the Computer , and software, it is suitable for both CW and pulsed lasers , wavelength range (300 – 1150 nm). A schematic of the experimental configuration block diagram is shown in Figure (1), while the experimental configuration setup is shown in Figure (2).

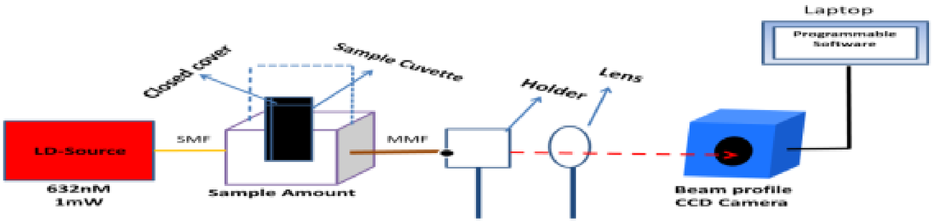


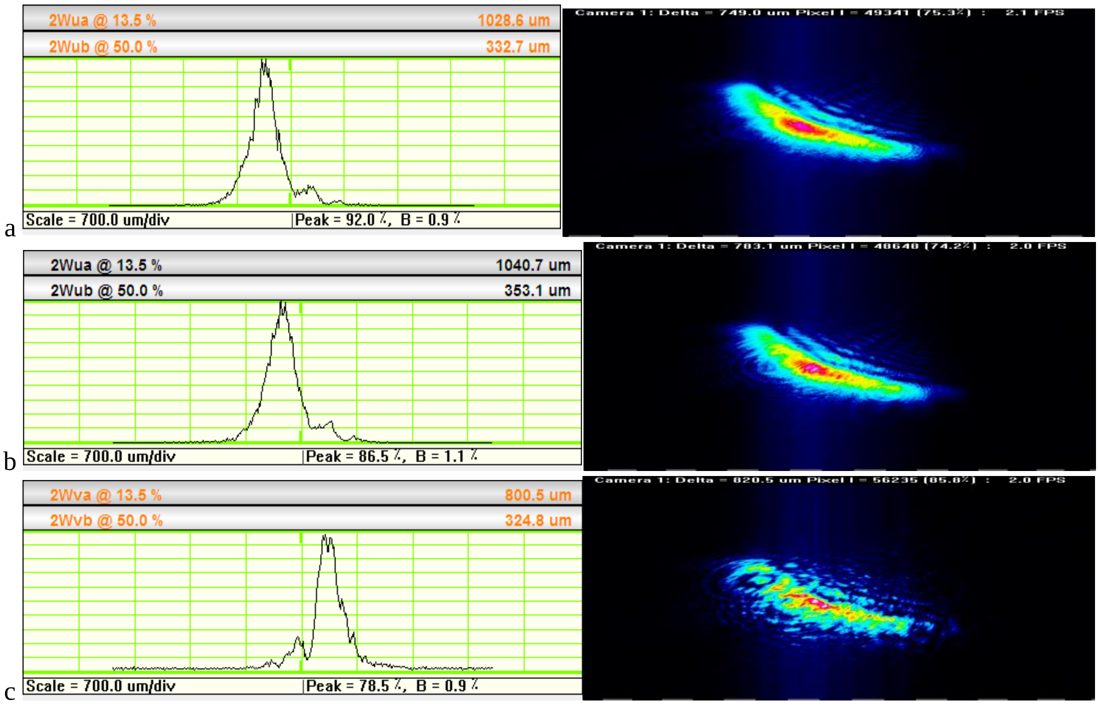
Figure 1: The experimental configuration block diagram.

Figure 2: The experimental configuration setup.

In order to use the multimode fiber as a spectrometer, we first calibrate the transmission through the fiber. Two specifications that have become increasingly challenging are resolution and spectral bandwidth. Photometric analysis requires a spectrophotometer with a 1.0 nm spectral bandwidth for regulatory compliance. While a smaller spectral bandwidth generates high quality data.

IV. RESULTS AND DISCUSSION

From the experimental setup which was illustrated above at an operating wavelength 632nm coupled with single mode fiber was used as LD source for a fiber based spectrometer measurements based on intensity modulation technique for various concentrations of Sucrose range from 10% to 50%. A shift of the input LD wavelength modifies the propagation constant causing the guided modes to accumulate different phase delays as they travel along the fiber, and thereby changing the speckle pattern. Figure (3) shows the different concentration Sucrose solutions spectrum comprise using 1 meter MMF while Figure (4) the same comprise using 1meter SMF.



d

e

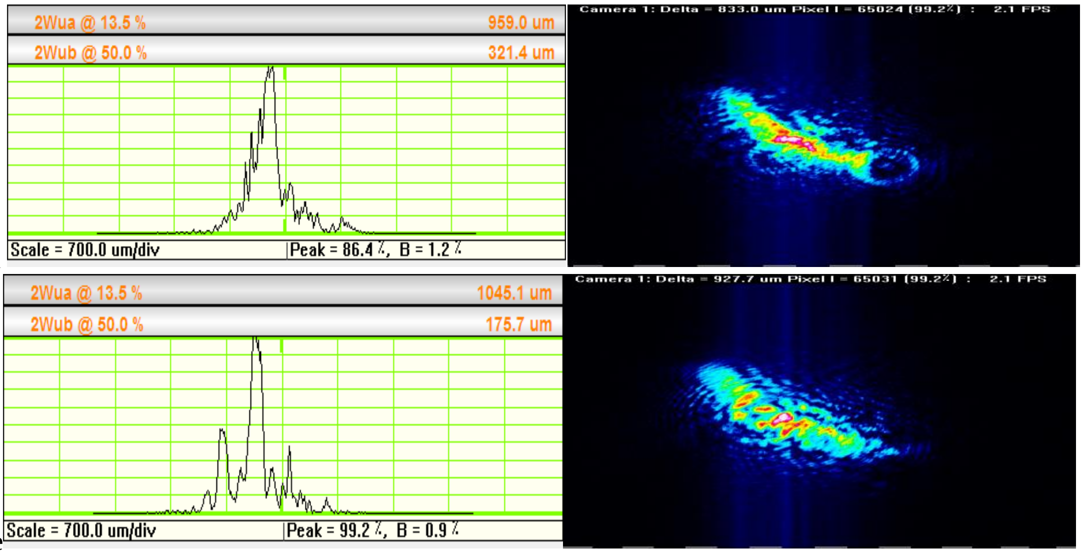


Figure (3): Different Conc.(a:10%,b:20%,c:30%,d:40%,e:50%) Sucrose solutions spectrum (left) and speckle pattern (right) using: 1-meter MMF.

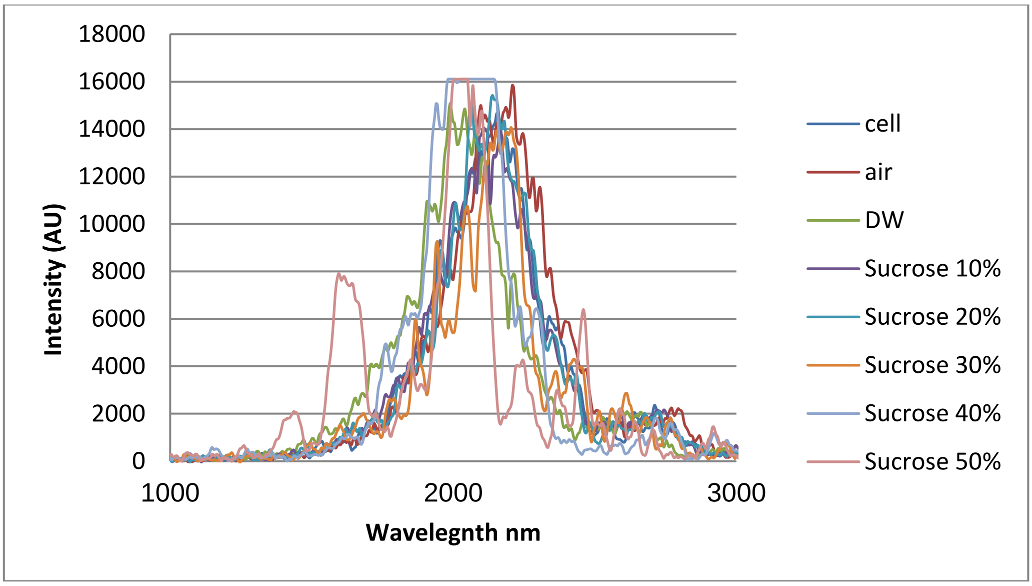


Figure (4): Different Conc. Sucrose solutions spectrums comprise using: 1-meter MMF.

As a summarization to discussions of our measurement results. An important factor in a spectrometer is the photon detection efficiency. Various methods can be used to improve the collection efficiency. A multimode fiber spectrometer, consisting of a fiber and a camera, can provide high spectral resolution and large Bandwidth while maintaining a small footprint, with a simple wavelength correction to improve the stability of the ultrahigh resolution fiber spectrometer against ambient temperature fluctuation.

Multimode fiber spectrometers offer clear advantages over traditional grating spectrometers. The most attractive feature is the ability to achieve high resolution with a compact size, with resolution currently only available in large benchtop system. In addition, optical fiber is extremely low cost, light weight, and has almost negligible loss over the lengths suitable for the spectrometer application.

In our implementation, in order to overcome the main limitation of the fiber spectrometer that the probe signal must be confined to a fixed spatial mode and polarization state to ensure that a given wavelength always generates the same speckle pattern. This was done by first coupling the probe signal to a single-mode polarization-maintaining fiber. This is analogous to the use of an entrance slit in a grating spectrometer, but the requirement for input to a fiber spectrometer is more restrictive. While the entrance slit in a grating spectrometer can be opened further to collect more light at the cost of lower resolution, exchanging the single-mode fiber for a few-mode fiber is more complicated.

V. CONCLUSIONS

The performance evaluation conclusions of fiber based spectrometer system show:

1. The fiber based spectrometer is designed to analyze the multi-line or broadband spectrum of light sources up to 10 nm for different sources like CW and pulsed lasers, super luminescence diodes, semiconductor laser diodes and LEDs.
2. In our implementation, we demonstrated that 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.

VI. REFERENCES

[1] Christopher, Palmer," Diffraction Grating Handbook ", 6th edition, Newport Corporation, (2005).
[2] Q. Hang, B. Ung, I. Syed, N. Guo, and M. Skorobogatiy, "Photonic bandgap fiber bundle spectrometer", Appl. Opt. 49, 4791–4800 (2010).
[3] B. Redding, S. M. Popoff, and H. Cao, "All-fiber spectrometer based on speckle pattern reconstruction", Opt. Express 21, 6584–6600 (2013).
[4] Z.Xu,Z.Wang,M.Sullivan, D.Brady, S.Foulger , andA.Adibi , "Multimodal multiplex spectroscopy using photonic crystals",Opt. Express 11, 2126–2133 (2003).
[5] T. W. Kohlgraf-Owens and A. Dogariu,"Transmission matrices of random media: means for spectral polarimetric measurements", Opt. Lett. 35, 2236–2238 (2010).