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PERFORMANCE ANALYSIS OF FIBER OPTIC SPECTROMETER

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ABSTRACT
The multimode optical fiber can be used as a high resolution fiber optic based spectrometer (FOS). After calibration the wavelength dependent speckle patterns produced by interference between the guided modes of the fiber. A performance analysis of the effects of the fiber geometry and length on the spectral resolution and bandwidth, also the additional limitation on the bandwidth imposed by speckle contrast reduction when measuring dense spectra has been demonstrated. A laboratory model using multi-mode optical fiber was designed and implemented for the purpose of spectral analysis based on the recording of the speckle pattern emerging from the other side of the optical fiber. Different prepared concentrations of both Sucrose and NaCl solutions samples tested by different approaches, high resolution and broadband fiber based spectrometer systems. The beam distribution can be represented by the speckle pattern, which can be detected by using a CCD camera placed at the end of the multimode optical fiber. The results of this study demonstrate the advantage of using a multimode optical fiber based spectrometer.

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 rely on a grating or prism to provide one-to-one spectral to spatial mapping in which different wavelengths are mapped to different spatial positions. For instance, the spectral resolution in a grating-based spectrometer scales with the optical path length, imposing a trade-off between device size and resolution. Over the past 20 years, miniature fiber optic spectrometers have evolved from a novelty to the spectrometer of choice for many modern spectroscopes. The advanced utility and flexibility provided by their small size and compatibility with a plethora of sampling accessories make this device a perfect choice for different chemical and biological analysis [1].

II. FIBER OPTIC BASED SPECTROMETERS OPERATION PRINCIPLE
The fiber-optic 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 because of its long propagation length, the minimal loss enable, high spectral resolution and good sensitivity [2, 3].

Figure (1- a & b) showed a designed setup for such fiber-optic based spectrometer and an expected speckle pattern recorded at the end of a (20 m) fiber as the input wavelength when scanned from 1500 nm to 1501 nm in the step of 0.01 nm. The speckle patterns de-correlate for very small changes in wavelength. Such high spatial-spectral diversity gives fine spectral resolution.

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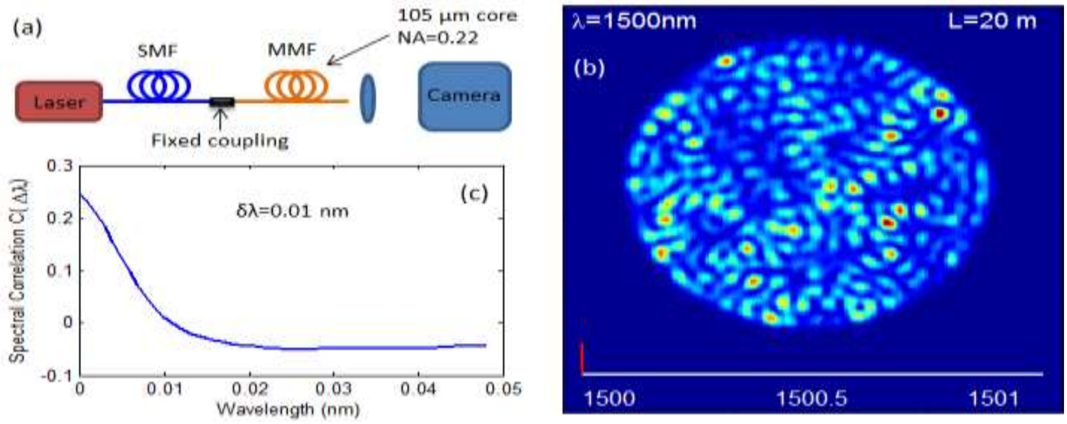

Figure (1): (a) - Designed Setup. (b) - Speckle pattern for expected results.

To use the fiber as a spectrometer, speckle patterns such as the ones shown in Figure (1-b) are recorded to construct the transmission matrix. After this calibration step, the tunable laser can be replaced by any optical source and the camera will record the speckle pattern. A reconstruction algorithm is then applied to recover the spectra of the input [4].

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 [5, 6,7].

III. EXPERIMENTAL SETUP

Two prepared sample solutions with two different substances (NaCl Salt & C12H22O11 Sucrose) were selected as solutes dissolved in distilled water with different concentrations.

In our research the fiber - based spectrometer consisted of a step-index multimode glass fibers with (NA=0.22), a core diameter of (62 µm), and a cladding diameter of 125 µm. The (1m, 5m, 10m) fibers used for the visible spectrometer was a silica core THORLABS fiber (FG105LCA), taking into account that to ensure that the input to the multimode fiber had the same spatial profile and polarization as the calibration a single-mode polarization-maintaining fiber used to couple the signal to the multimode fiber because if the probe signal had a different profile or polarization, it could excite a different combination of fiber modes with different (relative) amplitudes and phases, making the calibration invalid. In our experimental work the fiber-optic spectrometer have been done with two designs:

High Resolution Fiber based Spectrometer

Large core optical fibers can easily support hundreds to thousands of spatial modes. The speckle pattern produced by interference between these modes is determined by their relative amplitude and phase. For a monochromatic input light, the electric field at the end of a fiber of length L can be assume as the sum of the contribution from each guided mode. A shift of the input wavelength λ 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. To investigate the aforementioned effect, we assembled the test apparatus shown in the schematic diagram (2-a) and (2-b). A LD (632 nm) source was coupled with a single mode fiber and the collimated light is directed toward the sample's cuvette then received by the end of the multimode fiber under test which associated with the HR-2000 Optical Spectrum Analyzer (OSA). Power supply and data readout are accomplished with any PC via a USB interface. Depending on the bandwidth of the spectrum we can achieve the best achievable resolution. Specify your light source and we can choose the most fitting order of diffraction.

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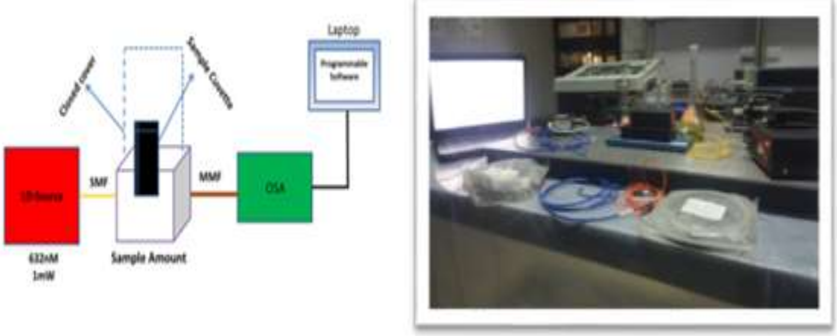

Figure (2): The schematic & Experimental diagram of Fiber based Spectrometer setup (OSA)

Broadband Fiber based Spectrometer

In addition to ultra-fine spectral resolution, multimode fiber spectrometers can also operate with very broad bandwidth, by demonstrated broadband operation in the visible Spectrum using a 5 cm long multimode fiber (65 µm diameter core, NA = 0.22). In order to calibrate the wavelength dependent speckle patterns in the visible spectrum, we used a broadband supercontinuum light source in combination with a monochromator. The monochromator selected a narrow band of the supercontinuum emission which was first coupled to a multimode fiber and then with another multimode fiber. To illustrate the speckle patterns formed by different colors, we used a color charge-coupled-device (CCD) camera to record red, green and blue speckles at the end of the multimode fiber, as shown in the schematic diagram (3-a) and in Figure (3-b). In the actual calibration and testing of the fiber spectrometer, a monochrome CCD camera was used. From the number of speckles, we estimated that ~700 spatial modes were excited in the multimode fiber.

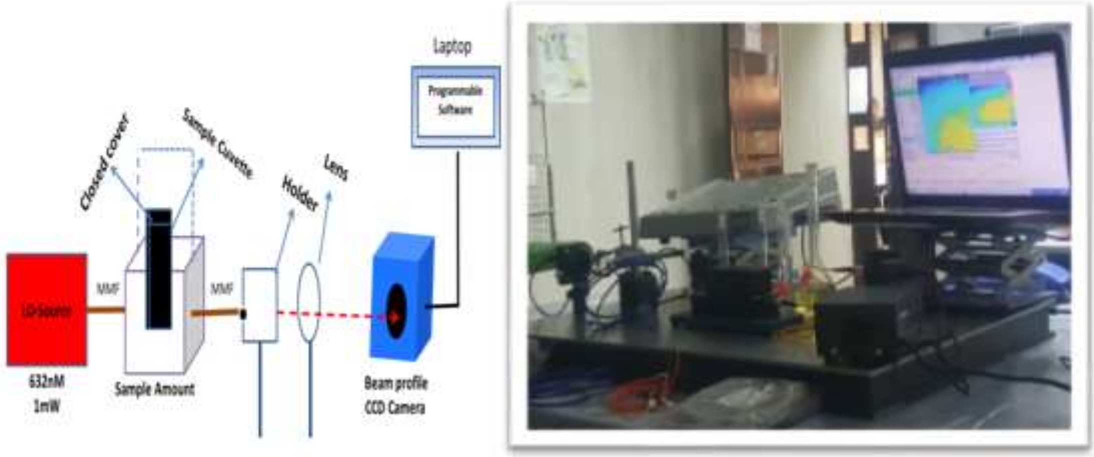

Figure (3-a): The schematic & Experimental diagram of MMF based spectrometer

e observed that the spectral correlation width scaled linearly with the fiber length up to 10 meters, confirming that mode coupling has a negligible effect on the spectral resolution of the fiber spectrometers. In order to push the resolution limit of the fiber spectrometer, we selected a 10-meter long, step index multimode fiber which fixed for mechanical stability and sensitive to environmental perturbations. As a result, light travelling in the fiber experiences slightly different propagation constant. In a sufficiently long fiber, the change in ambient temperature can add up to a significant change of the phase delay and alter the speckle pattern. Since our fiber spectrometer relies on a given wavelength consistently producing the same speckle pattern, changes in temperature would corrupt the reconstruction process.

IV. RESULTS AND DISCUSSION

High Resolution Fiber based Spectrometer

A fiber based spectrometer measurements based on intensity modulation technique have been done for various concentrations of NaCl range from (5% to 25%) and Sucrose range from (10% to 50%). A shift of the input LD wavelength modified 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 (4-a) showed the different concentration NaCl solutions spectrums comparison using (1-meter) MMF, while Figure (4-b) the same comparison used (1-meter SMF). Also a comparison between two types of fibers (SMF & MMF) with same length (1-meter) shown in Figure (4-c). While in case of increasing fiber length used in a fiber based spectrometer, an enhancement in spectral resolution appeared as shown in Figure (4-d).

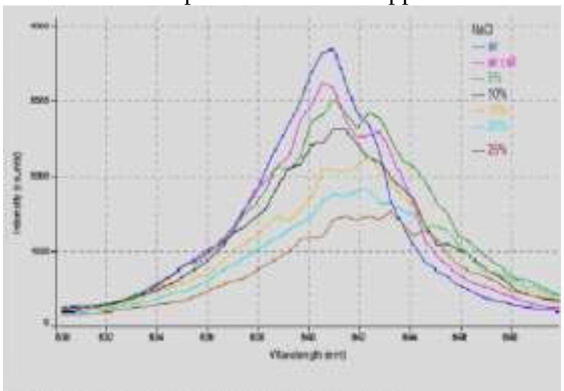

Figure (4-a): Different Conc. NaCl solutions spectrums comprise using: 1-meter MMF.

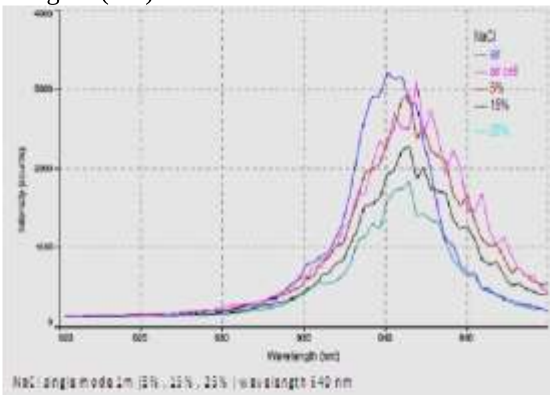

Figure (4-b): Different Conc. NaCl solutions spectrums comprise using: 1-meter SMF.

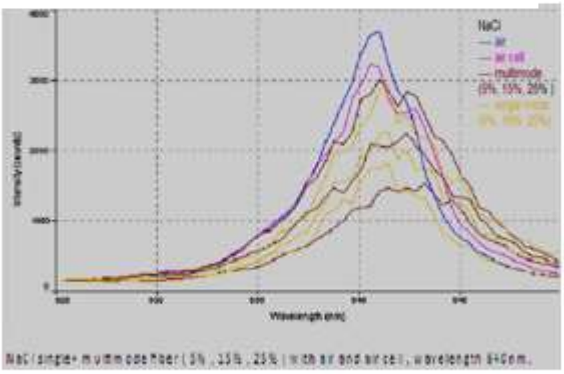

Figure (4-c): Different Conc. NaCl solutions spectrum comparison between using (1- meter) SMF & MMF.

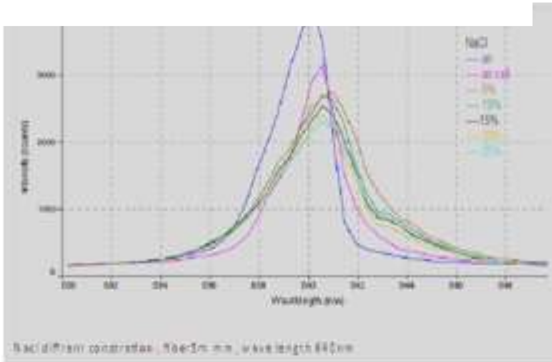

Figure (4-d): Different Conc. NaCl solutions spectrum using: 5-meter MMF.

Moving to Figure (5-a) showed the different Concentration in case of Sucrose solutions spectrums comprise using (1-meter) MMF, while Figure (5-b) showed the same comprise using (1-meter) SMF. As comprise between two types of fiber used with same length 1-meter shown in Figure (5-c). While in case of increasing fiber length used in a fiber based spectrometer, an enhancement in spectral resolution as shown in Figure (5-d).

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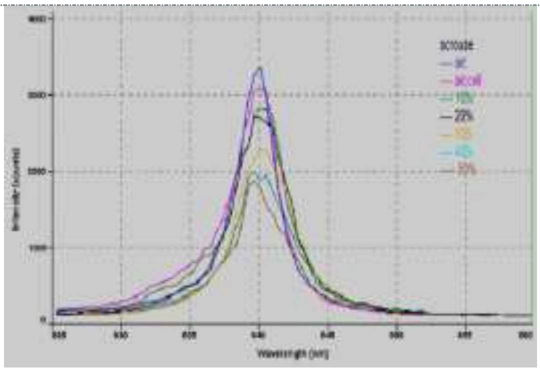

Figure (5-a): Different Conc. Sucrose solutions spectrums comprise using: 1-meter MMF.

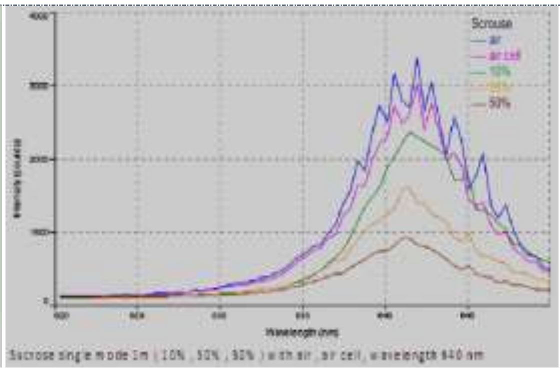

Figure (5-b): Different Conc. Sucrose solutions spectrums comprise using: 1-meter SMF.

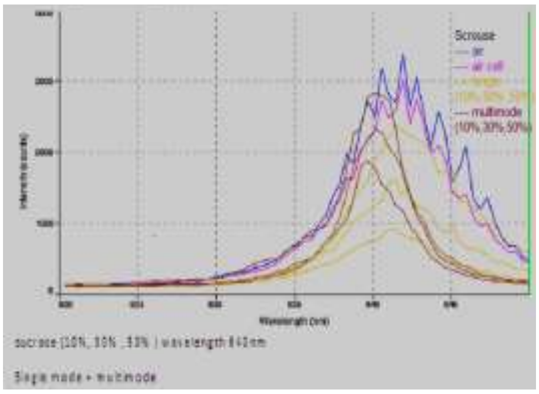

Figure (5-c): Different Conc. Sucrose solutions spectrums comprise between using (1 meter) SMF & MMF.

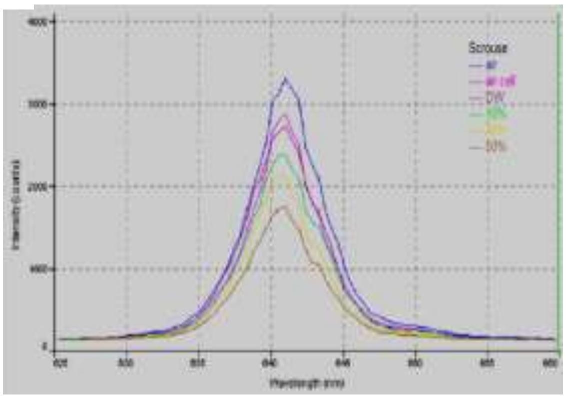

Figure (5-d): Different Conc. Sucrose solutions spectrums comprise using: 5-meter MMF.

The proposed spectrometer consists only of the fiber and a camera that images the speckle pattern generated by interference among the fiber modes. Although 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 m long fiber, and 0.03 nm resolutions over 5 nm bandwidth with a 5 m fiber. The insertion loss is less than 10%, and the signal-to-noise ratio in the reconstructed spectra is more than 1000.

Broadband Fiber based Spectrometer

From the previous explained fiber based spectrometer measurements experimental setup based on intensity modulation technique for various concentrations of Sucrose range from 10% to 50%, and NaCl range from 5% to 25%, a changing in the speckle pattern appeared due to the shift in the input LD wavelength modified the propagation constant causing the guided modes to accumulate different phase delays, as they travel along the fiber. Figure (6) showed the different Concentration Sucrose solutions spectrums using (5-meter) MMF in addition to speckle pattern image from beam profile CCD camera for each concentration.

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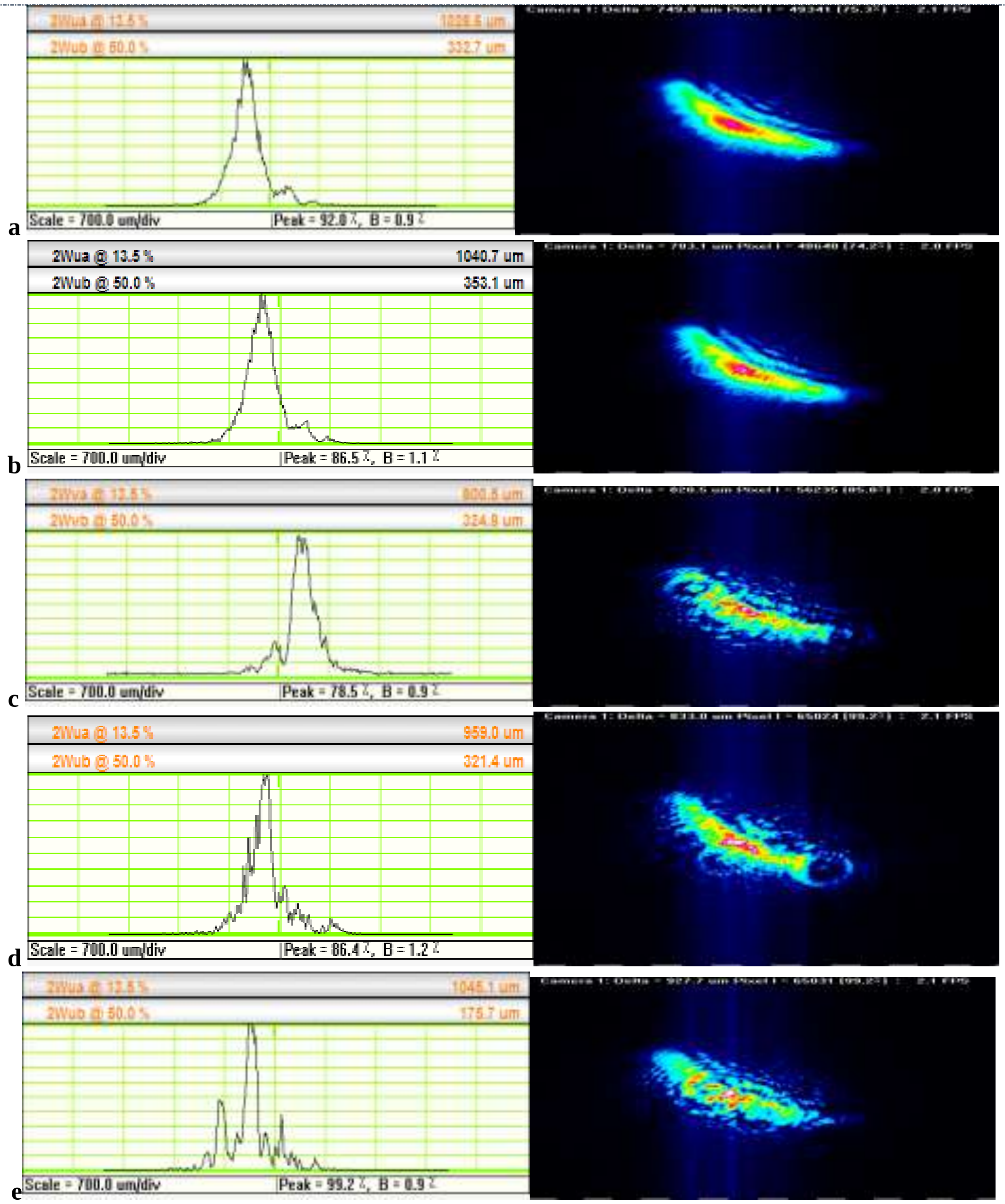
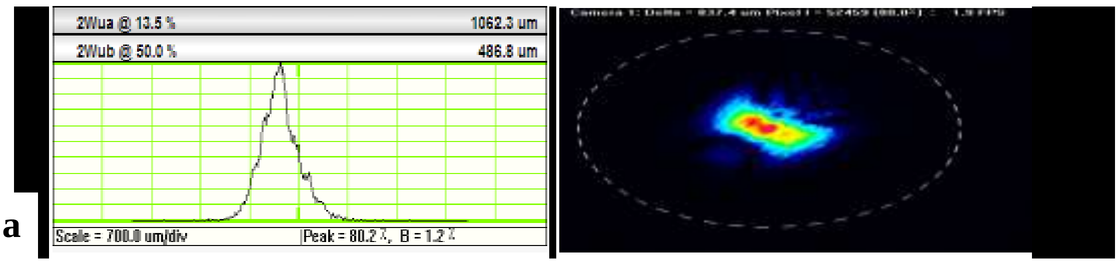


Figure (6): Different Conc. (a: 10%, b: 20%, c: 30%, d: 40%, e: 50%) Sucrose solutions spectrum (left) and speckle pattern (right) using: 5-meter MMF.

While Figure (7) showed the different Concentration NaCl solutions spectrums using (5-meter) MMF in addition to speckle pattern image from beam profile CCD camera for each concentration.



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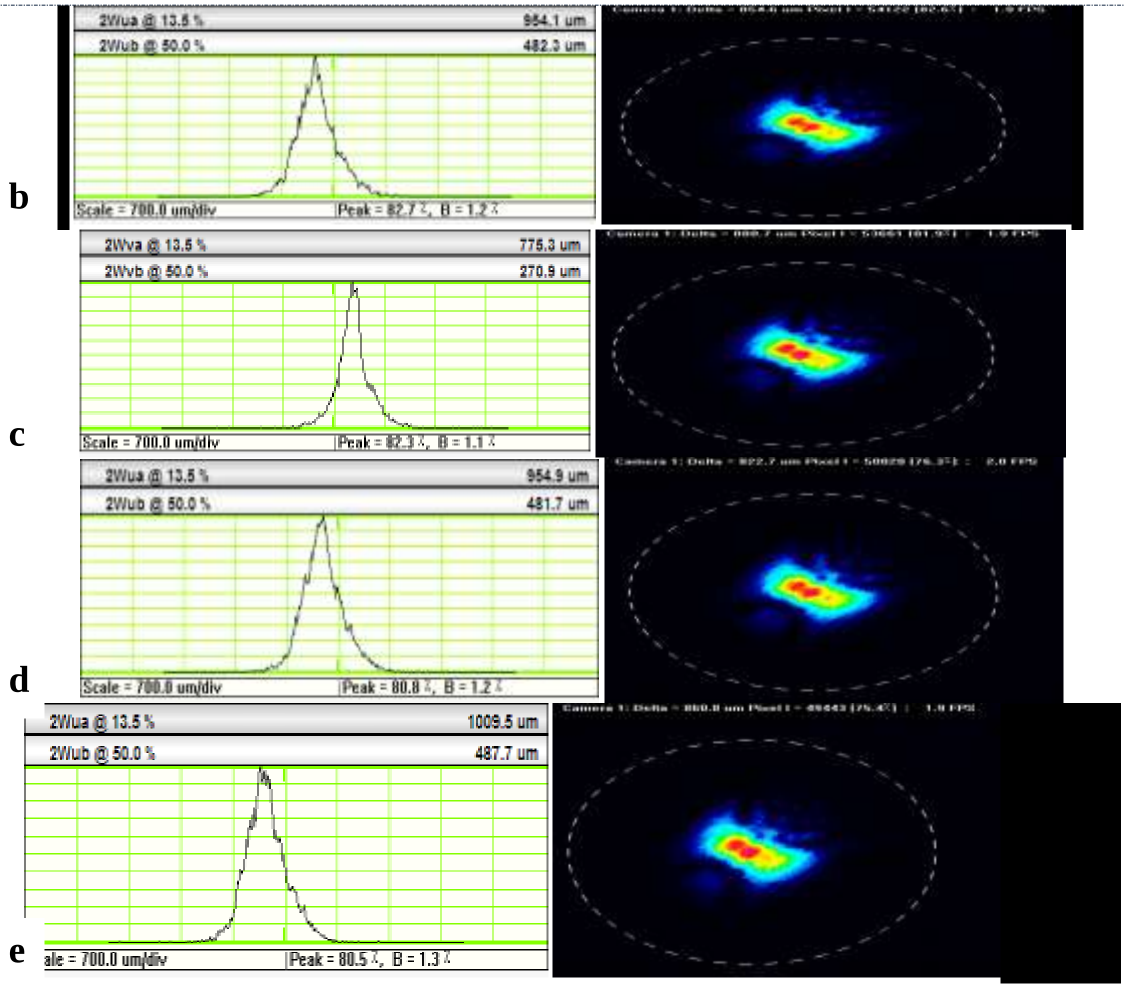

Figure (7): Different Conc.(a: 5%, b: 10%, c: 15%, d: 20%, e: 25%) NaCl solutions spectrum (left) and speckle pattern (right) using: 5-meter MMF.

As a result multimode fiber spectrometers offer clear advantages over traditional grating spectrometers due to an important factor which is the photon detection efficiency, with a simple wavelength correction to improve the stability of the ultrahigh resolution fiber spectrometer against ambient temperature fluctuation. Also the most attractive feature is the ability to achieve high resolution with a compact size, with resolution currently only available in large bench top 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 order to overcome the main limitation of the fiber spectrometer, we must tacking into account that the probe signal should be confined to a fixed spatial mode and polarization state to ensure that the given wavelength always generates the same speckle pattern. This was done first by coupling the probe signal to a single-mode polarization-maintaining fiber. This was similar 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 that 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. A high resolution, low loss spectrometer can be implemented in a multimode fiber with a 2D-CDD camera. The long propagation length of light in the fiber results in high spectral resolution, and the large core diameter enables broadband operation. Crucially, the fiber length and core diameter can be increased without significantly affecting the insertion loss of the spectrometer. Finally, 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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