FrinGOe: A Spectrometer-On-the-Go

1. Introduction

Our vision is to equip the man-on-the-street with a spectrometer to uncover the world of spectroscopy in their daily life. The success of achieving this vision lies in various key factors: the affordability, the accessibility and the usefulness of such a spectrometer. Although spectroscopy has greatly contributed to mankind in terms of space exploration, the discovery of new drugs, the development of new light sources and many others, the usefulness of spectroscopy in our daily life has yet to be demonstrated and many potential applications remain untapped. Currently, there is no clear approach to proliferate such spectrometers to the public due to the lack of a low cost, accessible and convenient-to-use spectrometer. FrinGOe aims to circumvent the issue of cost and accessibility.

Accessibility does not only imply portability but also its presence and ease of use whenever and wherever one needs it. A 2013 worldwide survey revealed that there are 96 mobile phone subscriptions for every 100 people. Mobile phones have now become an indispensable part of our lives and they are readily accessible to us on a 24/7 basis. Thus the implementation of an all-time accessible spectrometer can leverage on the mobile phone as the starting platform. To mitigate the high cost and make spectrometers affordable, we advocate a ***passive*** "add-on" to the mobile phone camera, and to utilize the processing power of its embedded computer and its display to present the spectroscopic information.

There are prior works to convert mobile phone into a spectrometer using dispersive optics add-on such as the diffraction grating or optical prisms. Due to the minimum length required for light dispersion by diffraction, the spectrometer often results in being too bulky with an odd-shape that cannot fit into the pocket. This reduces the desire to carry it around for spectroscopic exploration. Moreover, it consumes the entire imaging capability of the mobile phone camera. In addition, there are other engineering issues such as intolerance to mechanical misalignment of the diffraction grating and low optical throughput that results in a low signal-to-noise ratio.

The ability to "pocketize" the spectrometer will make a significant difference in engaging the public to adopt spectrometry in their daily lives. FrinGOe proposes a Fourier Transform Infra-Red implementation to perform spectroscopic measurement using the camera on the mobile phone. This allows an all-passive and compact add-on attachment just like a conventional mobile phone protective cover.

2. Conventional Fourier Transform Infra-Red Spectrometer (FTIR)

Fourier Transform Infra-Red (FTIR) is an option to perform spectroscopic measurements. It is widely deployed to measure the spectrum of thermal radiation of wavelengths between 3 - 14 microns with good spectral resolution and signal-to-noise ratio. Figure 1 shows a conventional optical configuration of FTIR.

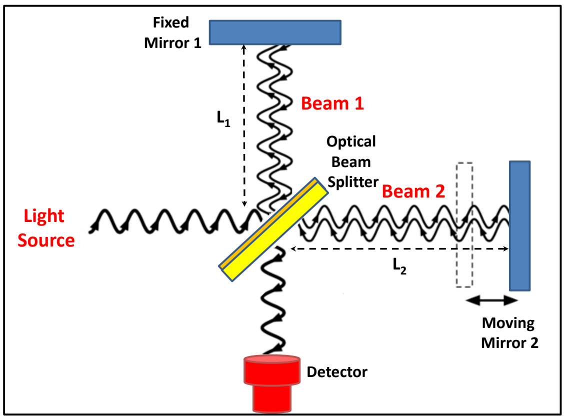

Figure 1 : Scanning FTIR interferometer

Monochromatic light of wavelength λ entering the FTIR, is split by the optical beam splitter into two beams of equal power. Beam 1 travels a distance of L_1 to Mirror 1 and reflects back while Beam 2 travels a distance of L_2 to Mirror 2 and reflects back. Through the round trips, Beam 1 accumulates a phase of $\frac{2\pi(2L_1)}{\lambda}$ while beam 2 accumulates a phase of $\frac{2\pi(2L_2)}{\lambda}$. Therefore, they have a phase difference of $\Delta\phi = \frac{2\pi(2L_2-2L_1)}{\lambda}$.

Both beams meet again at the optical beam splitter and interfere. Depending on their phase difference, the wave interference determines the power measured by the detector and the power reflected back to the source. For example, if the two beams are in phase at the detector, they superimpose constructively and the detector measures the maximum power. On the other hand, if they are out-phase by π at the detector, they interfere destructively and the detector measures no power while all the power is reflected back to the source. In general, for a phase difference of $\Delta\phi$, the measured power by the detector is proportional to $cos^2\frac{\Delta\phi}{2}$. This optical configuration is well-known to the optics community as the Michelson interferometer.

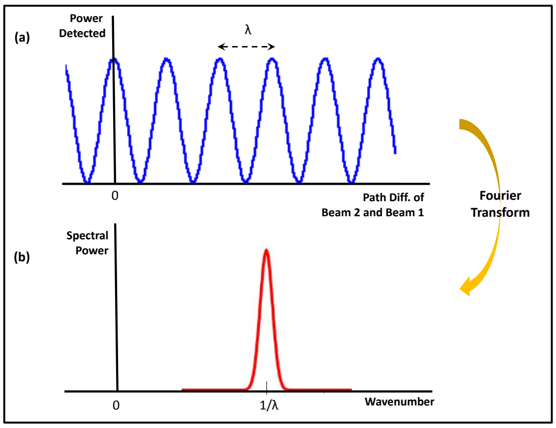

Figure 2: Sinusoidal interferogram for a monochromatic light of wavelength λ and its corresponding spectrum in wavenumber

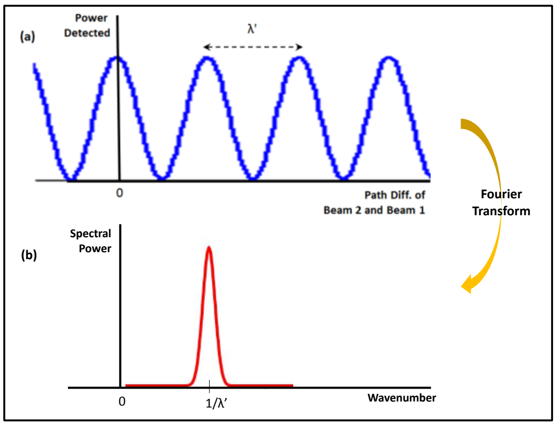

Figure 3: Sinusoidal interferogram when wavelength change to λ' and its corresponding spectrum in wavenumber

In a conventional FTIR spectrometer, one of the mirrors, say Mirror 2, is placed on a translational stage to be scanned over a distance while the other mirror is fixed. For every scan position, the detector records a measurement. To understand the working principle of FTIR, let us consider the case of Mirror 2 scanning away from the beam splitter. When Mirror 2 moves away from the beam splitter, the path difference between Beam 2 and Beam 1 increases, and so does their phase difference $\Delta\phi$. The power measured by the detector (see Figure 2a) will modulate sinusoidally (i.e $\propto cos^2\frac{\Delta\phi}{2}$) as Mirror 2 moves. This power modulation repeats itself for every λ increment in the distance travelled by Beam 2. The variation of detected power with path difference in Figure 2a, is known as the interferogram of FTIR. If a Fourier Transform is performed on this sinusoidal interferogram, a spectrum with only a single peak at a wavenumber of 1/λ is obtained, as shown in Figure 2b. With this, the wavelength of the monochromatic light entering the FTIR can be deduced.

If the wavelength of this monochromatic light is now changed to λ' and the scanning of Mirror 2 is repeated. The interferogram observed will again be sinusoidal, but with a different period, λ'. In other words, the power measured by the detector now repeats itself for every λ' increment in the distance travelled by Beam 2 (see Figure 3a). Likewise, the Fourier Transform of this sinusoidal interferogram will reveal a single peak, but at a different wavenumber, 1/λ' (see Figure 3b). Through this, FTIR tells us that the wavelength of the light has changed from λ to λ'.

In most operation of FTIR spectrometer, the spectrum-of –interest is mostly not monochromatic, and has many spectral components (i.e. λ_1, λ_2, λ_3…. λ_N). When Mirror 2 scans, each wavelength component "constructs" its own sinusoidal interferogram. Each sinusoidal interferogram has a period that depends solely on the wavelength, and an amplitude that depends on the power available in that wavelength. As the detector is unable to distinguish the individual contributions from each wavelength, it sums up the individual contributions of all wavelengths at every scan position of Mirror 2. Figure 4 shows the resultant interferogram measured by the detector. It is the sum of all interferograms contributed by each wavelength. Only when the path difference between Beam 2 and Beam 1 is zero (i.e zero phase difference), all individual contributions are at their maximum, thus adding up to give a sharp peak in the resultant interferogram. When the path difference deviates from this zero path difference, these contributions average out to a roughly constant value, thereby showing a small variation in the resultant interferogram. It is worthwhile to note that the broader the spectrum of light, the narrower the envelope of this modulation near the zero path difference. By performing a Fourier Transform of this resultant interferogram, it reveals the individual spectral components and their respective power. In essence, FTIR measures the spectrum of light by performing Fourier transform on the interferogram obtained from a scanning Michelson interferometer.

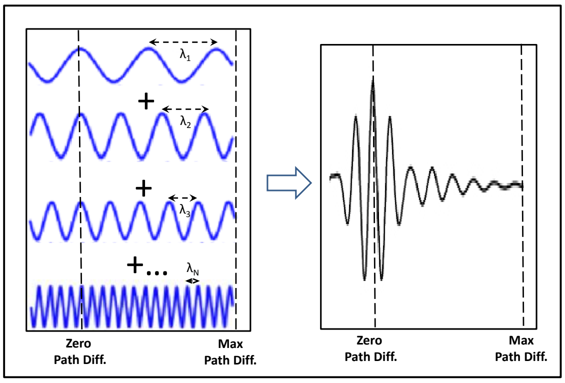

Figure 4: Resultant interferogram for light with broadband spectrum

For any spectrometer, a key performance specification is the spectral resolution. Spectral resolution is a measure of its ability to resolve features in the spectrum. A small spectral resolution is desirable due to its ability to resolve very fine spectral features. The spectral resolution of a FTIR spectrometer depends on the maximum path difference achievable in the scan. Referring back to our previous case of monochromatic light λ entering the FTIR, if the maximum path difference between Beam 2 and Beam 1 achievable in the scanning of Mirror 2 is Mλ, we will observe M number of cycles in the sinusoidal interferogram (counting from the zero path difference). Upon Fourier Transform, the spectrum reveals a single peak at the wavenumber of 1/λ. As the sinusoidal inteferogram does not extend to an infinite path difference, this peak is not a perfect Dirac delta function. The truncation of the sinusoidal interferogram at a maximum path difference of Mλ, gives this peak a width of ~1/(Mλ) in terms of wavenumber. When one converts the wavenumber into wavelength, this corresponds to spectral wavelength resolution (full-width) of ~ λ/M at wavelength λ.

The same spectral resolution relationship applies to FTIR in measuring broadband light spectrum. As a rule of thumb, to find the spectral wavelength resolution of a FTIR at a particular wavelength λ, we use the maximum path difference of the scan, divide it by the wavelength to get a factor M, the spectral wavelength resolution is then given by ~ λ/M.

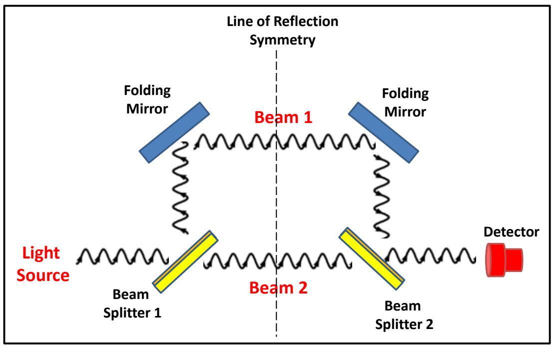

Figure 5: Mach Zehnder interferometer

3. To build an equivalent non-scanning FTIR interferometer

To develop a low cost, all-passive and compact FTIR attachment to the mobile phone camera, it necessitates the removal of mechanical scanning. FrinGOe realises this in two steps. The first step is to introduce an equivalent optical configuration of the Michelson interferometer as shown in Figure 5. The two beams after the first beam splitter is directed to travel in the forward direction and re-combine in the second beam splitter. Depending on the path difference travelled by Beam 1 and Beam 2, there is a phase difference that similarly determines the power measured by the detector after the second beam splitter. Intuitively, if the interferometer is folded along the dotted line of reflection symmetry in Figure 5, it looks like a Michelson interferometer. Thus these two interferometers are equivalent with similar physics and the same sinusoidal interferograms generated by monochromatic light. This configuration is known to the optics community as the Mach Zehnder interferometer. The second step is to create an array of such Mach Zehnder interferometers, each with its own detector and a different value for the path difference, as shown in Figure 6. From the power measured by these detectors in parallel, an interferogram can be constructed, whereby the Fourier Transform yields the spectrum of the light. In this way, FTIR spectroscopy without mechanical scanning is achieved.

As mentioned earlier, the maximum path difference determines the spectral resolution of FTIR spectroscopy. It is desirable to have a large maximum path difference since this gives a better spectral resolution. However, to handle a large maximum path difference, more detectors are needed in this non-scanning implementation. Let us estimate the number of detectors required to achieve a spectral wavelength resolution of 1 nm at λ=400 nm. Since the spectral wavelength resolution is given by ~ λ/M, we need M=400 to yield a 1nm resolution. This sets the required maximum path difference to be 0.16 mm which gives 400 cycles in the sinusoidal interferogram (counting from the zero path difference). At least two detectors are required to sample a cycle effectively. Therefore, more than 800 detectors are needed to sample a good interferogram whose Fourier Transform can yield spectral wavelength resolution of 1nm at λ=400nm. A typical sensor array in the modern mobile phone camera has >3000 by >2000 pixels. Thus a single row of pixels in the detector array is more than sufficient to give the spectral resolution illustrated in our example.

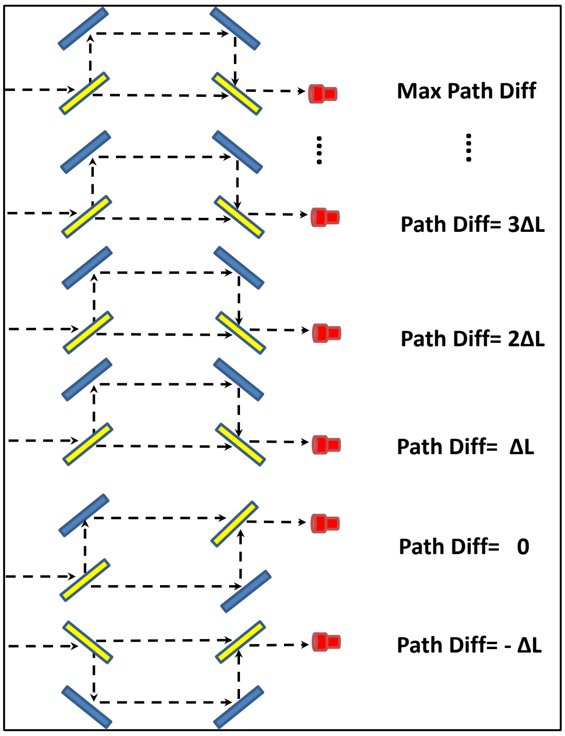

Figure 6: Array of Mach Zehnder interferometers with path difference fixed at different values.

4. FrinGOe: The art of building compact non-scanning FTIR spectrometer with low noise and good spectral resolution

FrinGOe uses innovative crystal technology to create a low cost 2D array of Mach Zehnder Interferometers and patented optical configuration to map the array onto the camera sensor. This allows an all-passive and compact optical add-on (as small as 4mm by 4mm by 2mm) that can be mounted onto any imaging platforms such as a mobile phone camera, Raspberry Pi camera or other OEM devices as shown in Figure 7.

A typical mobile phone camera has a sensor resolution of 3264 by 2448 pixels (8 MegaPixel). The 2D interferometer array of FrinGOe utilizes every pixel to perform FTIR spectroscopy. Each row of the sensor array is used to produce a 3264-points interferogram, and 2448 interferograms are captured in one snapshot. Although the Fourier Transform of one interferogram is sufficient to produce the spectrum, Fourier Transform is applied on each of the 2448 interferograms to obtain 2448 spectra for averaging so as to produce a final spectrum with extremely low noise. This is equivalent to performing 2448 repeated scanning of the conventional FTIR for spectrum averaging. Spectrum averaging is very effective in noise reduction, and in the case of FrinGOe, it is attained in one snapshot.

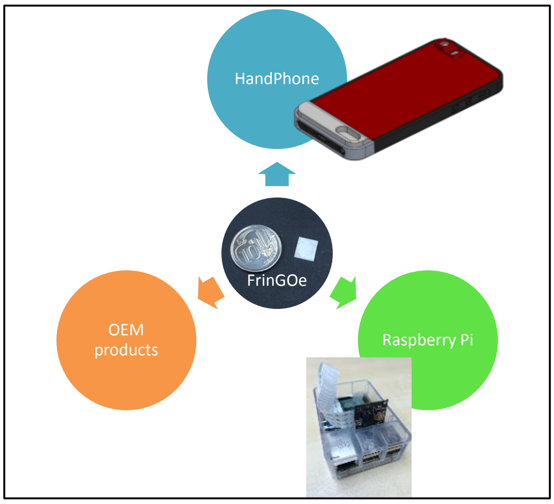

Figure 7: FrinGOe optics and the type of platforms it can be mounted.

Figure 8 shows the 2D interferogram image captured by a 8 megapixel camera sensor of an iPhone 5s with FrinGOe. The light source is a 635 nm red laser. Since this is a quasi-monochromatic light, each row of the image reads a sinusoidal interferogram and there are more than 2000 such sinusoidal interferograms in one image. These interferograms collectively show regularly spaced lines called fringes. Pixels that lie on the same fringe detect interference with the same path difference. By performing Fourier transform on each row and taking their averages, Figure 8 shows the spectrum of the 635 nm red laser. In this preliminary demonstration, our constructed FrinGOe has 167 fringes from the zero path difference, thus giving 167 cycles in each interferogram. This yields a theoretical wavelength spectral resolution of ~ 4 nm @ 635nm.

Figure 9 shows the image when the same FrinGOe is measuring a broadband halogen light source. As expected, due to the broad spectral bandwidth, the intensity modulation is only observable near the zero path difference, thus accounting for the few clear fringes in the image. This is unlike the case of monochromatic light where fringes span the entire image. Figure 9 also shows the corresponding processed spectrum of this halogen light source from the FrinGOe.

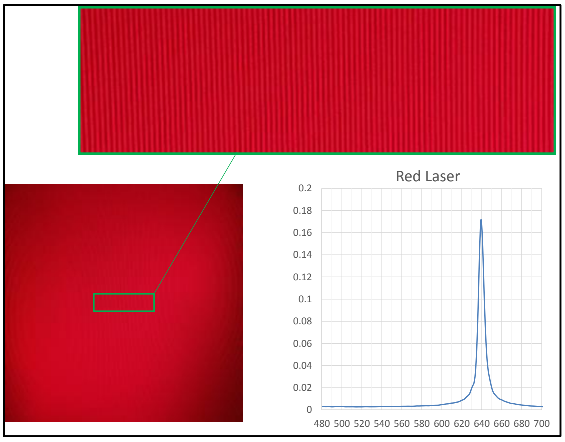

Figure 8: FrinGOe image of fringes of red laser and its processed FTIR spectrum

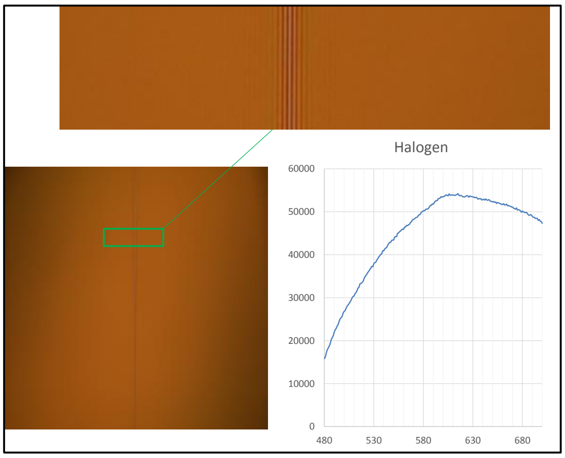

Figure 9: FrinGOe image of fringes for halogen light and its processed FTIR spectrum

Another recent prototype of FrinGOe has around 400 fringes from the zero path difference. It is designed to give a wavelength spectral resolution of ~ 1 nm @ 400nm. Figure 10 shows the measured spectra of various light sources and filtered light using this 400-fringe FrinGOe on an iPhone 5s camera.

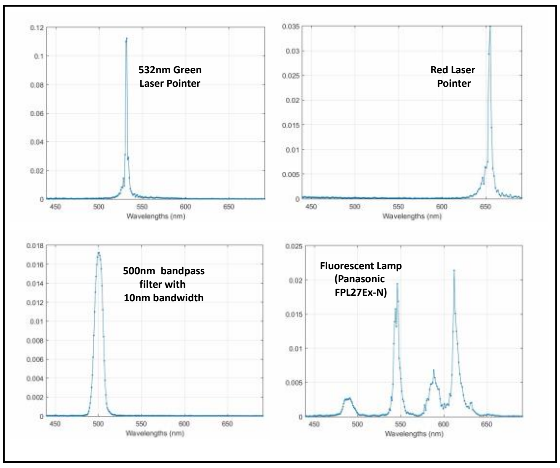

Figure 10: Examples of measured spectra using 400-fringe FrinGOe on iPhone 5s camera

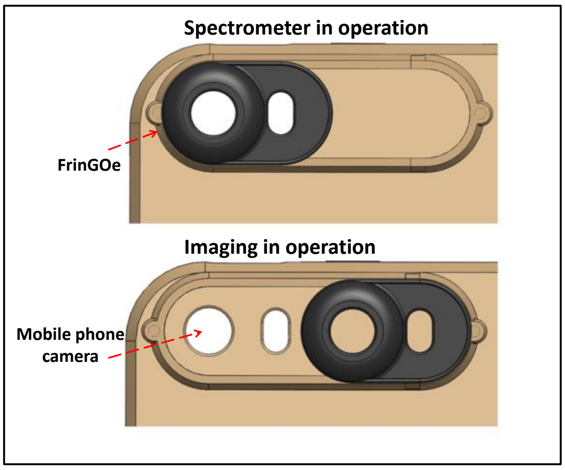

Figure 11: FrinGOe switchable between spectroscopic and imaging mode

Intrinsic robustness of FrinGOe's Mach-Zehnder crystal array gives good tolerance to temperature changes and to mechanical misalignment. This allows FrinGoe to be adjustable between an operational position where it is positioned in front of the camera, to a nonoperational position where the camera can function normally as shown in Figure 11. In this way, the imaging capability of the mobile phone camera is not compromised and users can have both spectroscopic and imaging functionality coexisting on their mobile phone.

5. Summary

In our quest for a Spectrometer On-The-GO, we demonstrate a low cost, all-passive, and compact FrinGOe add-on to mobile phone camera. We use innovative 2D Mach-Zehnder crystal array to achieve non-scanning Fourier Transform Infra-Red spectroscopy with fine spectral resolution and extremely low noise. The invention allows "pocketizing" of a high quality spectrometer so that it is remarkably convenient to carry around while running a daily routine. This low cost, all-time accessible and convenient-to-use spectrometer will help to engage the public in adopting spectrometry in their daily life, establish an objective language in communicating colours, and allow all man-on-the-street to participate in the exploration of new spectroscopic applications.