# Construction of a low-cost laser-based multiplexed spectrometer: a potential probe for environmental pollution monitoring

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**Abstract:** A low-cost, sensitive, laser-based (Helium Neon; He-Ne) optical Fourier-transformed (multiplexed) spectrometer has been constructed for the quantification of suspended particulates in the air. The optomechanical features of the spectrometer are presented together with a theoretical framework of its operation. The apparatus is calibrated by using a standard commercial spectrophotometer and has been successfully used to detect smoke of various densities. The simplicity in the design of the apparatus and sensitivity in its measurement would expectedly attract high school and college students and definitely help to spread the awareness of environmental pollution among younger generation.

**Keywords:** laser; optical instrument; low-cost design; environmental pollution measurement; multiplexed spectrometer.

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## 1 Introduction

Breathing polluted air over a long term can increase a person's risk of dying from lung cancer or heart and lung disease. Investigators evaluated data from a long-term study of 1.2 million people (Pope et al., 2002). Data for about 500,000 of these individuals was linked to information on air pollution, vital status and cause of death through 1998. Researchers have identified a strong link between outdoor air pollution and heart attacks. A study (Poloniecki et al., 1997) in England estimates that 1 in 50 coronaries treated in London hospitals may be triggered by air pollutants, such as nitrogen dioxide, sulphur dioxide, carbon monoxide and black smoke. Many of these deaths might be avoided with better control of pollutants, particularly motor vehicle exhaust emissions. The above statistics was just a glimpse of the rising levels of air pollution in the globe. Sometimes it is difficult to know that suspended particles and toxic chemicals pollute the air in and around us. The environmental monitoring systems in vogue are normally very expensive and have huge statures. In this respect, the challenge is to design an inexpensive, portable system that would facilitate the on-site detection of pollutants.

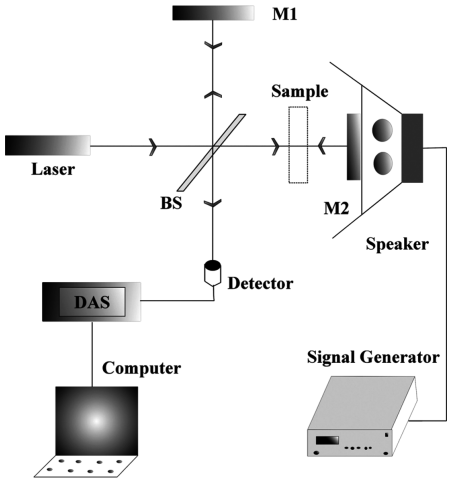
In this paper, we have designed and constructed a scanning Michelson's interferometer (with a moving mirror), which is compact and reasonably sensitive to detect suspended particulates in the air. A time-dependent interference pattern in the output detector of the interferometer is the result of continuous variation of path difference between two interfering beams. The system is popularly known as "multiplexed spectrometer", which means that it will scan all frequencies at the same

time and will hence gain advantage in time, Felgett's advantage (Vanasse and Sakai 1967; Fellgett, 1949, 2006). The Fourier transformed interferogram (power spectrum) is the output signal of the constructed apparatus. The measurement of Optical Density (OD) using our apparatus is in close agreement with that of a good-quality commercial spectrophotometer. From the power spectra of a sample with various concentrations measured by using the constructed spectrometer, it has been shown that the OD varies linearly with the concentration of the sample (Beer-Lambert law).

## 2 Experimental details

The optical and mechanical components of the constructed apparatus along with ray paths are shown in Figure 1. The setup is basically a Michelson's interferometer. One mirror (M1) is fixed and the other (M2) mirror moving. The moving mirror is mounted on a speaker that is connected to the signal generator. The speaker cone is made to vibrate at the frequency of the signal generator. In the operation of the apparatus, we always kept the frequency of signal generator to be 8 Hz. The light from the laser source (He-Ne) falls on the beam-splitter and gets bifurcated into two parts. One part goes straight to the M2 mirror after being transmitted by the beam-splitter and the other being reflected by the same moves toward the M1 mirror. Both the beams retrace their paths and come again to the beam-splitter and an obvious interference pattern results in the detector. The interference signal from the detector is fed into a home-made, low-cost miniaturised Data Acquisition System (DAS). The electronic components of the DAS (12-bit resolution, KIT 118) were purchased from Ocean Controls (USA) and assembled. The DAS module is connected into the parallel printer port (LPT1) of a computer and is controlled by software, which is written in QBASIC. The acquired signal data were further analysed by using commercial software Microcal Origin$^{TM}$. The power spectrum of the time-dependent interferogram signal was obtained by Fast Fourier Transformation (FFT) analysis of the signal. The whole setup may be assembled in an optical bread-board of $1' \times 1.5'$ area. However, position of M2 mirror is very crucial in the case of measurement of environmental pollution as beam of M2 has to travel the environment under test.

**Figure 1** The apparatus: Components and ray diagram of our constructed system



The optical path difference (OPD) created by the translating mirror M2 (Figure 1) is

$$x = 2L, \tag{1}$$

where x is twice the distance L travelled by M2. A derivation (Vanasse and Sakai, 1967) of the specific intensity $I_k(x)$ observed in the interferogram for a radiation of single wavenumber $k$ ($=2\pi/\lambda$; $\lambda$ is the wavelength of the incident radiation) gives,

$$I_k(x) = \frac{J(k)\langle T(k)\rangle}{2[1+\cos(kx)]}. \tag{2}$$

Here, $J(k)$ is the incident intensity and $T(k)$ is the beam splitter transmission function, which is averaged over polarisations and combined. For a particular incident intensity of wavelength $\lambda$ and specific optical components in the interferometer, $J(k)$ and $T(k)$ remain constant. Equation (2) can be rewritten as follows:

$$I_k(x) = \frac{A_0}{1+\cos(kvt)}, \tag{3}$$

where $A_0 = J(k)\langle T(k)\rangle/2$ and $v$ is the speed of change of OPD. The speed $v$ is directly related to the speed of scanning mirror M2. In this case, $v$ is two times the mechanical speed of M2. If $f$ is the frequency of the interferogram of a monochromatic light (single wavelength), then equation (3) can further be modified to

$$I_k(x) = \frac{A_0}{1+\cos\left(\frac{2\pi vt}{\lambda}\right)} = \frac{A_0}{1+\cos(2\pi ft)}, \tag{4}$$

where $f = v/\lambda$. Thus, the Fourier-transformed spectrum of the time domain interferogram signal (having only one frequency component) would show a single peak in the power spectrum.

It is to be noted that this system can in principle work with any monochromatic or even white light source to achieve Fellgett advantages (Fellgett, 1949, 2006). In the case of white light source, one may expect a number of power spectra, where each spectrum corresponds to spectral weightage of a particular wavelength in the optical source (Bloomfield, 1976). The sample concentration can be measured by following absorption or/and scattering modes. In the absorption mode, we need to use a wavelength ($\lambda$) of the monochromatic source close to the optical absorption band of the sample. For example, 1306.2-nm-light source may be used to detect the concentration of methane (Nelson et al., 1948) in the environment. In that case, the light beam to the M2 mirror may be exposed to open environment. If we consider the amplitudes of the power spectrum in absence or presence of the sample (methane) to be $I_0$ and I, respectively, the concentration (c) of the sample can be measured by using Lambert-Beer law (Ingle and Crouch, 1988, Houghton, 1977)

$$\frac{I_0}{I} = \exp(\varepsilon cl), \tag{5}$$

where $l$ and $\varepsilon$ are the light path through the sample and extinction coefficient of absorption of the sample. For almost all known pollutants, ε values are constant and can be found in literature (Lee et al., 2005). Thus, the concentration of the pollution can easily be measured.

To measure the concentration of a sample by using scattering mode, the samples should have some scattering efficiency to the light used ($\lambda$). This is also required that the sample should not absorb the light from the source ($\lambda$). Then, one may use the same formula (equation (5)) to estimate the concentration of the sample. However, the scattering extinction coefficient (Che et al., 2006) has to be used. In the case of a sample of suspended particulates having finite absorption in the light ($\lambda$) used, a complex extinction coefficient, which considers loss of light to the detector by absorption and scattering, should be used. In this study, He-Ne laser ($\lambda$ = 632.8 nm) was used as source and smoke (suspended particulates) as sample, which has insignificant absorption at 632.8 nm. It has also to be noted that the efficiency of scattering by suspended particulates with higher diameter appears at least $10^6$ times larger than that for the smaller particles. This is because large particles scatter much more light than small particles, as the intensity of scattering of a particle is proportional to the sixth power of its diameter (Rayleigh's approximation) (Sarkar et al., 2006). For example, the particulates of PM10 (thoracic fraction, ≤10 μM) and PM2.5 (respirable fraction, ≤ 2.5 μM) will be detected in the instrument. However, PM10 would offer much higher extinction coefficient to the measured OD, revealing more efficiency in particle detection.

## 3 Results and discussions

The time-dependent interferogram is shown in Figure 2, upper panel. As the laser wavelength (632.8 nm) is shorter compared with the distance travelled by M2 due to speaker vibration, it is quite sufficient to have number of maxima and minima in the obtained interference pattern as shown in Figure 2 (upper). The signal is numerically fitted using a function,

$$y = A_0 + [1 + A\cos(2\pi ft)], \tag{6}$$

where $f$ and $t$ are the frequency and time of the signal, respectively. $A_0$ and $A$ are two constants indicating offset and amplitude (at $t = 0$), respectively. From the numerical fitting of the acquired data, the values of $A_0$, $A$ and $f$ were obtained to be 640, 50 and 40, respectively. Note that the frequency of the interference signal (40 Hz) is much higher than that of the signal generator (8 Hz), which is responsible for the translational motion of the mirror M2. Thus, the possibility of direct interference of the later signal to the former one is negligible. We have also observed that the signal of frequency 40 Hz was completely disappeared when one of the interfering beams was blocked. This observation confirmed that the signal (40 Hz) is only due to interference of two beams. The power spectrum of the time-domain interferogram signal is shown in the lower panel of Figure 2. The decrease in amplitude of the signal upon insertion of absorbers (microscope glass slides of various opacities) is also evident from Figure 2.

We have also calibrated the measurement of OD of an absorber by using commercially available standard UV-VIS spectrophotometer (Shimadzu, model UV 2450), which relies on equation (5) for OD measurement. We define OD of an absorber

as log ($I_0/I$); $I_0$ and I are the amplitudes of power spectra in absence and presence of the absorber, respectively. Figure 3 shows the calibration curve. In the measurement, our sample was microscope slide (glass), and we varied OD of the sample by changing number of the slides in the optical path between the beam splitter and the mirror M2 (Figure 1). It is evident from the calibration curve that the error in the measurement is relatively lower when measured OD is smaller. However, the error lies between 30% and 40% of the measured OD. This study was further extended to detect smoke (suspended particulates) in the air. In this experiment, the optical path between the beam splitter and M2 was only exposed to the smoke and found distinct change in the measured OD with the variation in the concentration of the smoke (data not shown). The preliminary results indicate that the apparatus has very high sensitivity (~ppm). It has to be noted that limitation on the detection of the sample is very much dependent on the scattering extinction of the sample ($\varepsilon$) and the travel length of the beam to M2 through the sample, which will ultimately dictate the OD of the sample of interest. As shown in Figure 3, OD = 0.05 can easily be measured by this instrument.

**Figure 2** A comparative study of the interferogram (upper) and their power spectrum (lower) without attenuation and with glass slides of various opacities

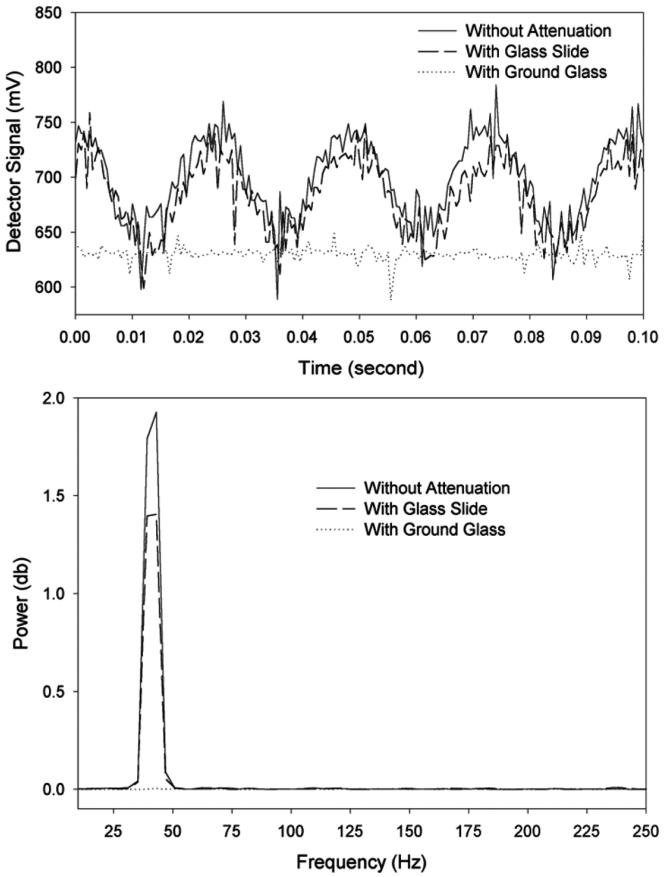
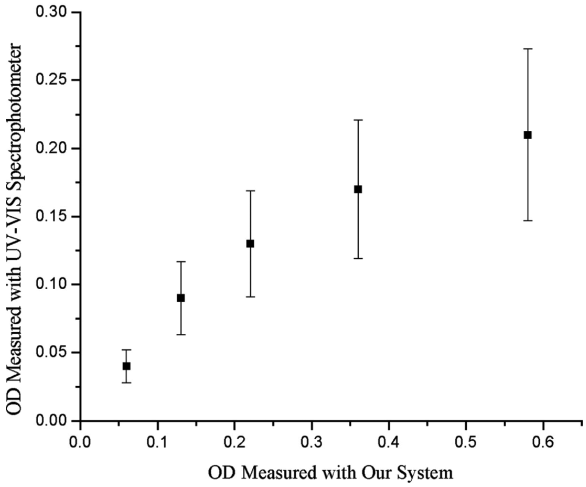


**Figure 3** A calibration plot showing the optical densities (OD) measured with our system and with UV-VIS spectrophotometer




## 4 Conclusion

We report our construction of a low-cost, Fourier-Transformed spectrometer with reasonably high sensitivity. A single wavelength (632.8 nm) He-Ne laser was used as a source and a variable path difference between two interfering beams were achieved by using a loud speaker. The constructed apparatus was calibrated using a commercially available absorption spectrophotometer (Shimadzu, Model UV 2450). The system was successfully used to measure OD of smoke, which is a good mimic of the air-suspended particulates and found reasonably high sensitivity. In principle, other pollutants like $NO_x$, $SO_2$ can also be measured by choosing the light source. However, designing a low-cost gadget to instill awareness of environmental pollution is the motive of this work. We are working toward modification of the system including the possibility of replacing He-Ne laser by a white light source. This modification would expectedly widen the application of the apparatus in measuring number of air pollutants quantitatively at the sub-ppm level.

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