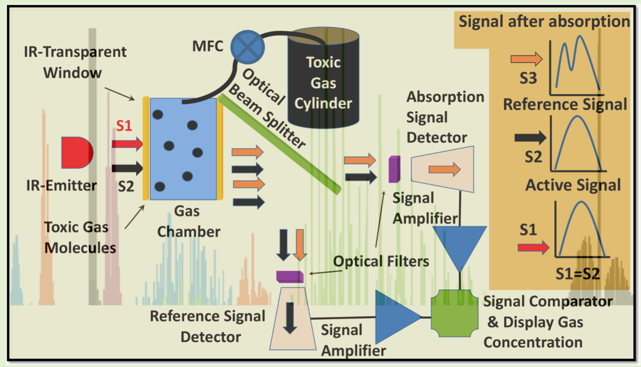
Non-Dispersive Infrared Gas Sensing Technology: A Review

Ravindra Kumar Jha, *Senior Member, IEEE*

***Abstract*—Non-dispersive infrared gas sensing (NDIR) is a unique optical sensing technique where IR radiation interacts with the targeted analyte and in the process, it is absorbed. This absorption is unique for every gas and hence, based on the absorption characteristics, gas molecules can be finger-printed and distinctively identified. A simple NDIR gas sensor consists of an IR emitter, detector, optical filter, gas cell, and circuit elements for signal processing. Further, these components also offer choice for selection for example a micro-electromechanical system (MEMS) based membrane heater, a light-emitting diode (LED), and IR lamp all have the capability of generating IR spectra. Similarly, a pyroelectric detector, photodiode, bolometer, as well as thermopile has the ability to detect IR rays. The choice of the selection of components carries advantages and disadvantages associated with them, and thus it is very important to choose them correctly for the targeted applications. This article reviews the evolution of non-dispersive infrared gas sensing techniques and the basic components of these sensors are discussed one-by-one. Finally, the shortcomings of the NDIR gas sensor have been summarized and the efforts made in recent times to cope with these are also discussed.**



***Index Terms*—Non-dispersive infrared, gas sensor, optical sensor, infrared emitter, infrared detector.**

I. Introduction

TRADITIONALLY, gas sensors find their application to detect various toxic, flammable, and combustible analytes, which may be released due to leakage or as a by-product. However, in the past two decades, these sensors have found various other applications such as in an HVAC (heating, ventilation, and air conditioning) system for indoor air quality monitoring, medical applications (breath analyzers for biomarker detection, incubation, neurosurgery, etc.), agriculture, and transportation to name a few. Many gas sensing techniques have evolved depending on the transduction technique, such as chemiresistive, capacitive, electrochemical, optical, etc. [1]. When compared on specific parameters such as selectivity, sensitivity, hysteresis, resolution, repeatability, optical gas sensors have an edge due to unique and distinguishable absorption properties of gas species [2]. There are various classes of optical gas sensors which include non-dispersive infrared (NDIR), photoacoustic spectroscopy (PAS), tunable diode laser absorption spectroscopy (TDLAS), and spectrophotometry. As the name suggests, in an NDIR gas detection system, optical dispersion of IR radiation is not needed. Hence, dispersive elements like diffraction grating are absent in such a gas sensor. It is the most straightforward yet most promising among all these techniques since most of the toxic gases demonstrate strong absorption in the mid-infrared regime (2.5 μm – 14 μm) due to fundamental transitions of molecular rotation and vibration energy states. In fact, the absorption of the gases in this regime is about 100 times more than that in the near IR region. This is because the near IR spectrum is basically an overtone of the mid IR spectrum which truly denotes the fundamental vibrations of the molecules. It should be noted that infrared light is usually absorbed by molecules having ‘dipole’ which is a characteristic of molecules where atoms are arranged non-symmetrically. It is also possible in molecules where the modes of vibration are non-symmetrical as the asymmetric stretching and bending of the molecules induce dipole moment. Symmetrical molecules like diatomic gases usually don’t get excited by IR light due to the lack of dipole generation by any means.

NDIR sensors history is relatively new and after the development of optical bandpass filter in the 1970s, the research in this direction showed a pace [3], [4]. Even though the research in the area keeps growing with time, it was yet to be publicly used may be due to its bulky nature and moving parts such as mechanical chopper. However, with

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The author is with the Sensors Laboratory, Department of Electronics and Electrical Engineering, Indian Institute of Technology Guwahati, Assam 781039, India (e-mail: jha@iitg.ac.in).

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time, the technology gained interest as well as the faith of common people due to which, the next decade saw several applications of NDIR gas sensors such as in various oil and gas industries, coal mines, pharmaceuticals, automobile industries, etc. These devices were based on new designs and were integrated with low-cost microprocessors, available till that time. We can call this era as conversion of NDIR sensors from mechano-optical systems to purely electronics systems. Even though, the modern NDIR sensors offer a number of advantages in terms of high selectivity, sensitivity, low power consumption etc. there are usually three disadvantages which are still associated with it: the bulkiness of the device due to lens system, interference due to overlapping spectra of two gases, and the experimental limit of detection (ELOD) for the targeted analyte. To overcome these issues, a number of theoretical and experimental works have been done and the parameters responsible for these have been identified. For instance, ELOD is broadly dependent on the IR signal strength at the detector end and the signal-to-noise ratio [5]. The IR signal strength at the detector in turn depends on the IR source, IR detector, and the optical path it traverses before reaching the detector. Therefore, in designing an NDIR sensor, the design of individual components become very important. This article reviews the current NDIR gas sensors categorized based on the type of emitter, detector, or gas cell configuration. As an IR source, a regular incandescent lamp, compound semiconductor-based light-emitting diodes, and MEMS heaters are discussed while, as IR detectors we mainly focussed on thermopile, photodiode, pyroelectric, and bolometers. Seeing the current trend of evolution of gas cell designs, we have discussed face-to-face, planar, and cavity-type NDIR sensors. Finally, the pitfalls observed by different research groups and their remedies provided by them over the time are discussed.

II. Basic Principle

NDIR technique is the simplest absorption-based gas sensing technique which was demonstrated by Luft in 1943 for the first time. A basic NDIR gas sensor system can be visualized as an arrangement where an IR radiation is allowed to interact with gas molecules in a gas cell/chamber and the change in transmitted IR radiation is compared to obtain the concentration of the analyte. A schematic illustration of a typical NDIR gas sensor is shown in Figure 1. Generally, pulsed broadband IR rays are generated by the IR emitter. If we consider S1 (active signal) and S2 (reference signal) are IR signals generated at the source end, we can say that both are inherently the same as they are emitted from the same emitter (which is reflected in the shaded region of the figure). From the gas cell, we can expect in principle two signals either absorbed (S3) or non-absorbed (S1 or S2). The signals S2 and S3 are deflected towards two different optical filters i.e. one filter is dedicated to selectively detecting absorption spectra of the targeted gas (to selectively identify the absorbed signal S3) while the other filter is chosen in non-absorption spectrum region (to identify the actual signal S2 originated from IR emitter).

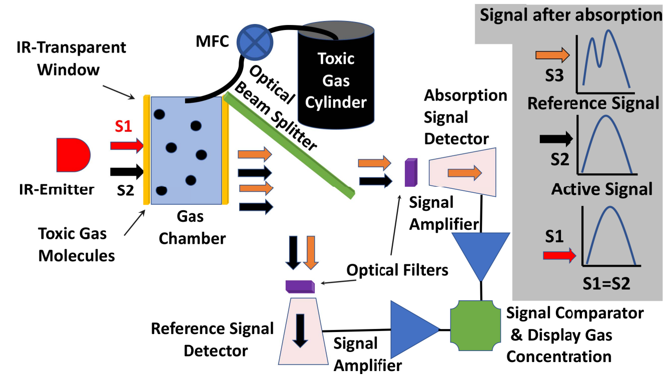

Fig. 1. Schematic diagram of NDIR gas sensing set-up.

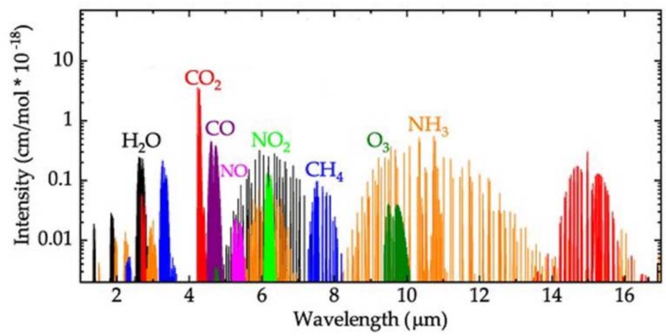

Fig. 2. Absorption spectra of gas molecules (color of the spectra is the same as the letters used for annotation of molecules) in the Mid-IR range. Adapted from [8], [9].

Both the signals are detected at the end and compared to identify the presence of a target gas quantitatively and qualitatively.

This can be explained on the basis of Beer-Lambert law as per equation (1).

$$I(\lambda) = I_o(\lambda)\, e^{-\alpha(\lambda)cl} \tag{1}$$

Here, $I(\lambda)$, and $I_o(\lambda)$ are the intensities of detected and emitted radiation respectively at a particular wavelength λ and its unit is W/m^2. $\alpha(\lambda)$ is the gas absorption coefficient (product of gas concentration and specific absorptivity of the gas), 'c' is the gas concentration, and 'l' is the path length.

The absorption spectra for the volatile organic and inorganic gases are shown in Figure 2. It is clearly evident that except strong absorption signature of non-toxic water vapors H_2O), most of the toxic gases like carbon dioxide (CO_2), carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), methane (CH_4), ammonia (NH_3), and ozone (O_3) has an absorption in this range. Gases whose absorption spectra lie in the range of 2 μm – 8 μm receive strong interference from water vapors [6]. However, the optical filters with narrow bandpass spectra help the devices to get rid of this problem to a certain extent. In fact, not only water vapors, the NDIR sensors also face strong interference from other analytes [7]. In these cases, calculating channel-to-channel interference coefficients (as shown in Equation 2) are very helpful.

The equation (2) is shown below:

$$k_{xy} = \frac{\beta_y}{\alpha_y} \tag{2}$$

where, k_{xy} is defined as interference coefficient, α_y is the absorption coefficient of gas y, and β_y is the absorption coefficient of gas y within gas x.

III. Classifications of NDIR Gas Sensors Based on Components

An NDIR gas sensor can be classified into different types based on the IR Emitter, IR detector, and gas cell topology as follows

A. Based on IR Emitter

The IR source is a very important and fundamental requirement of an NDIR gas sensing system. The key requirement of a good source is its ability to emit IR rays in the required wavelength range, the emitted IR light's strength to reach the detector end (without dying out in the gas cell), and its modulation capability at a good pace for high sensitivity lock-in detection. The stability and resistance towards external ambient conditions-, short- and long-term drift, etc. Broadly, LED, MEMS heater, and Lamp are the three types of sources for an infrared generation where the lamp is categorized as a divergent source whose emitted light is usually scattered.

1) NDIR Gas Sensor With Lamp as IR Emitter: Micro bulb lamp sources were conventionally the first choice in NDIR gas sensors due to their simplicity, low cost, and high spectral emission (2 mW/steradian in a 4% bandwidth) [10]. Although it is difficult to direct IR emission from a filament-based lamp onto the detector due to its attenuation in the path by multiple reflections, they are still finding their position in NDIR sensors. Schröder *et al.* used a single wire (diameter = 25 μm) Kanthal (FeCrAl) alloy filament to obtain IR spectrum in the range of 1 – 15 μm [11].

They proposed this source for the deployment in NDIR ethanol (9.5 μm) and carbon dioxide (4.26 μm) detection. Wang *et al.* developed an NDIR CO_2 sensor using an incandescent lamp coupled with two thermopile detectors [12].

The IR lamp was operated at 5V and 0.1 A while pulsed every second at a duty cycle of 50%. Diharja *et al.* developed an NDIR carbon monoxide (CO) gas sensor using these incandescent bulbs as infrared sources operated at lower power ratings [12]. The IR source they used required a maximum voltage of 2.5 V and 0.3 A current. For constant output light intensity, they used a current source to power the IR emitter which utilized an LM 317 regulator circuit. Jun *et al.* developed a portable NDIR methane detector utilizing this type of IR emitter and pyroelectric detector [13]. The lamp frequency was set to be 4 Hz for proper toggling of the lamp as well as for providing sufficient time to allow the detector to read and stabilize the voltage. Wilson et. al employed two different IR sources i.e. a commercially available incandescent bulb (from Oshino) having tungsten filament and a MEMS-based broadband IR emitter (from Axtris AG) in NDIR CO_2 detection with a fixed pyroelectric detector (Pyreos Ltd) [14]. The IR lamp was operated in pulse mode and driven by a 5 Hz square wave current source (with a maximum current of 0.086 A). The frequency was finalized at 5 Hz since the maximum optical power can be obtained with the fastest repetition at this particular frequency. If the frequency is further increased or decreased, it impacts the average output power. Unfortunately, due to their bulkiness and power-hungry nature, their use is limited. Further, these emitters are mostly confined within 5μm by the lamp glass cover itself. Therefore, alternative IR emitters are being developed.

2) NDIR Gas Sensor With MEMS Heater as IR Emitter: Membrane heaters such as microelectromechanical system (MEMS) based devices have recently gained attention for NDIR gas sensors due to their high energy efficiency, greater reliability, faster response, low thermal mass, smaller size, and its compatibility with the CMOS foundry process. It is usually installed with a collecting and reflecting cup so that the light can be projected precisely on the detector. Vincent and Gardner developed a hand-held CO_2 sensor based on MEMS silicon-on-insulator (SOI) wideband IR emitter which was coupled to a thermopile detector via a 4.26 μm bandpass filter [15]. The device could operate for a wide CO_2 concentration range of 50 ppm – 25000 ppm with an accuracy of ~2.9%. Xing *et al.* developed NDIR based acetone and ammonia sensor using silicon-based plasmonic infrared emitter [16]. The emitter used in the device is an array of extruded cylindrical plasmonic structures which help in enhancement in infrared radiation at selective wavelengths corresponding to the aforesaid analytes (8.26 μm for acetone and 10.6 μm for ammonia). The targeted gas concentration is 50 -200 ppm for acetone while for ammonia they could detect as low as 10-20 ppm. Leuthold *et al.* designed a CO_2 gas sensor (0 – 50000 ppm CO_2) which utilizes a thermal mid-IR source by combining MEMS heater with metamaterial perfect heater structures [17]. The structure of the emitter has a great impact on the performance since the device showed a 5-fold enhancement (at a fixed emitter-to-detector distance of 4 mm and a thermopile detector) in relative sensitivity as compared to the blackbody emitter-based sensor. Song et. al used MEMS technology to fabricate a square patterned narrowband (narrowband peak width$\left(\Delta\lambda/_{\lambda}\right) = 0.16 – 0.23$) IR emitter for filterless detection of dimethyl ether ($(CH_3)_2O$) gas [18]. The IR emitter is based on $TiN/SiO_2/TiN$ trilayer sandwich structure and the wavelength of the emitted light can be tuned by varying the surface pattern. Since thermal emission of an IR emitter is directly proportional to its emissivity and in turn proportional to its absorptivity (according to Kirchhoff's law and at a particular wavelength, temperature, and emission angle), it can be said that a good absorber is also a good thermal emitter. A CMOS compatible semiconducting or dielectric material has a low absorption coefficient (in most of the toxic gas absorption range in the IR fingerprint range) and hence couldn't be considered as a good emitter. Metal structures are good absorbers while a flat sheet of metal used in thermal emitter has poor absorption and good reflection abilities. Therefore, Pusch *et al.* applied nano-plasmonics and metamaterial principles to design a good plasmonic IR absorber and in turn good thermal emitter as shown in Figure 3(a),(b) [19]. They fabricated a periodic hexagonal array of tungsten cylinders on a microheater with the structure embedded in SiO_2 membrane as shown in Figure 3(c). This type of structure encourages coupling between light and surface plasmons and the latter is

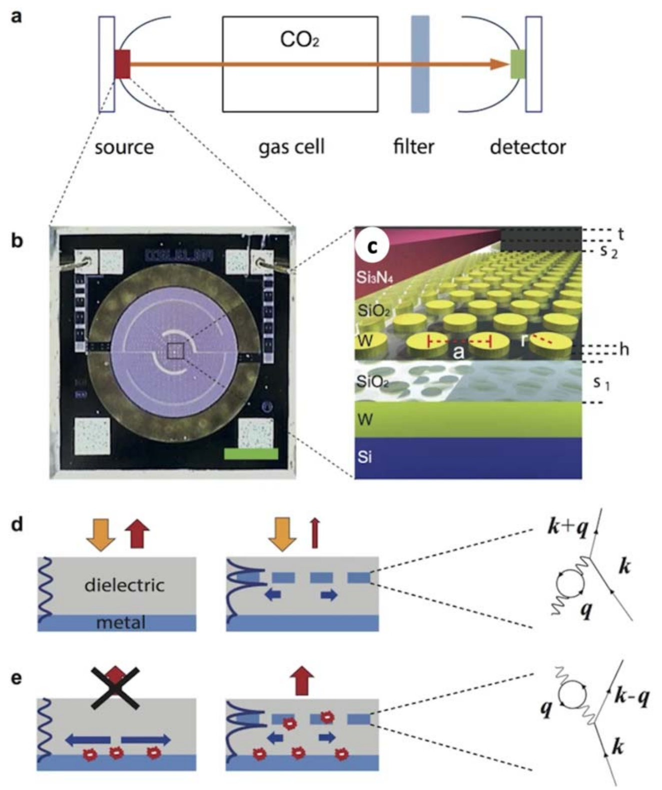

Fig. 3. (a) NDIR gas sensor arrangement (b) optical image of IR emitter (scale 200 μm) (c) schematic diagram of the cross-section of the emitter with the plasmonic crystal structure (dimensions: s_1 = 1500 nm, h = 500 nm, s_2 = 200 nm, and t = 550 nm) (d) Absorption: In an IR emitter, a part of the incoming light is absorbed when it passes through the dielectric, while in the plasmonic crystal device the light is trapped in a plasmonic mode and the plasmons are subsequently absorbed in the electron gas, which is shown as a scattering process between a surface plasmon with wave-vector q and an electron with wave-vector k. (e) Emission: Plasmons are spontaneously generated in the heated tungsten surface but they couple to the external light-field only in the presence of a plasmonic crystal structure.

absorbed due to collision between electron as well as phonon as shown in the schematic diagram in Figure 3(d). In this type of IR emitter, the surface plasmons are emitted spontaneously to the tungsten surface and out-couple to the external field as shown in Figure 3(e).

Here, the radius of the tungsten cylinders, and inter cylinder distance governs the tunability of surface plasmon resonance. By using this structure, the emission intensity of the thermal emitter at 4.26 μm is enhanced almost four-fold and hence signal-to-noise ratio of the NDIR CO_2 sensor is improved significantly.

3) NDIR Gas Sensor With LED as IR Emitter: With the efforts in the research and development in the area compound semiconductor physics, it is possible now to develop light emitting diodes in the IR region. This has enabled researcher to replace IR source in the NDIR gas sensors with IR-LEDs with added advantages such as intrinsic safety, speed of operation, extension of wavelength range beyond the glass cut-off at 4.5 μm, better signal-to-noise ratio, improved accuracy, and less stabilization issues [20], [21]. Several efforts have been put in recent times to develop LED based NDIR sensors.

Gibson et. al developed a wireless NDIR based carbon dioxide sensor with the help of industry which is based on a narrow bandgap III-V LED source with a photodiode detector [21]. The narrowband III-V LED and photodetector was produced by epitaxial growth under ultra-high vacuum from independent and individually controlled material sources for maintaining the stoichiometry. This allows tuning the spectral characteristics of both the emitter and detector by changing the ratio of the III-V stoichiometry and hence, it has the potential to be replicated in sensing other gases as well. Mahbub *et al.* developed a lightweight and compact NDIR methane sensor with a rapidly pulsed near-infrared light-emitting diode (with an emission maximum wavelength $\lambda_{max} = 1.65$ μm, (Lms16LED-R, Alfa Photonics, Latvia)) as an IR emitter [22]. The authors have pointed out that the NIR LED (1.3 – 2.3 μm) has better thermal management abilities as compared to mid-IR LEDs (3.3 – 5 μm) due to the higher energy gap of infrared semiconducting materials. The LED source was operated at a very low duty cycle (0.2%) at an operating frequency of 1 kHz and 1.8 A of maximum forward current.

B. Based on IR Detectors

There are a number of IR detectors reported for NDIR gas sensors. These detectors have role to convert electromagnetic radiation energy or temperature differences into readable electrical signals.

1) Thermopile Detectors: Thermopile is a device which detect thermal radiation based on the Seebeck effect. It is made up of a serial combination of several thermocouples which map the temperature difference between a cold and hot junction into a measurable voltage.

A micromachined thermopile detector is preferred to reduce the cost, and power consumption of the NDIR sensor while maintaining its efficiency. Rubio *et al.* [23] developed a non-selective NDIR sensor (targeting VOCs such as acetone) where the detector was made-up of two arrays one is of filters and the other an array of thermopile detectors. The filter array is fabricated using the Fabry-Perot approach where PECVD grown SiO_2 and polysilicon layers are grown alternatively. The thermopile array was made up of a bulk micromachined nitride membrane. The array of filters and that of thermopile detectors are bonded using the flip-chip technique. The responsivity of the thermopile elements in the array was 17 $\pm$ 0.4 V/W while the noise equivalent power is maintained at 0.95 nW. The goal of designing such a sensor is to reduce the cost of the device particular incurred on selective filters. The broadband filter combined with the thermopile detector array produces a voltage pattern which is predicted for particular gas and concentration based on multivariate regression technique. Yoo *et al.* [24] designed and fabricated an NDIR CO_2 sensor using an integrated thermopile detector on a similar micromachined silicon nitride membrane. The thermopile with absorber layer had a sensitivity of 30 V/W which was increased to 51 V/W when it was packaged with Fresnel lens. The $\sim$1.7 times increment in the sensitivity is due to a decrease in thermal mass and heat loss from the hot junction.

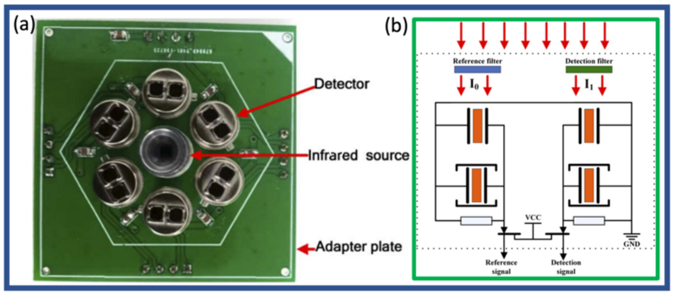

Fig. 4. (a) Integrated dual channel pyroelectric detector (b) schematic of this detector. Adapted from [28].

Although, thermopile detectors have a fast response time, however, the noise levels in the output are severe and therefore, pyroelectric detectors come into the picture as they have at least one magnitude fewer noise levels.

2) Pyroelectric Detectors: Pyroelectric element changes its lattice constant by absorbing heat energy since due to pyroelectric effect, electrical polarization varies with the lattice constant and they are related as per equation (3)

$$\Delta \vec{P} = \vec{p_T}.\Delta T. \tag{3}$$

where, $\vec{P}$ is electrical polarization, $\vec{p_T}$ is the pyroelectric coefficient, and T is absolute temperature [25].

Pyroelectric detectors are well-known detectors utilized in gas sensors owing to their cost-effectiveness and resolution when targeted for Mid-IR spectrum beyond 7 μm [26]. The added advantage of this detector is the non-requirement of any active cooling at room temperature.

Frodl and Tille [27] utilized two lithium tantalite pyroelectric detectors with a responsivity of 640 V/W and electrical noise of 600 nV in the development of a CO_2 sensor where two sources were used for precision enhancement. Pyroelectric detectors have also been very effective in designing multiple gas sensors. Liu *et al.* [28] designed a six analyte (CO, CO_2, CH_4, H_2CO, NH_3, and NO) detector using dual channel pyroelectric IR detector. The arrangement of the six dual-channel detectors around the centrally place IR emitter and integrated with adapter plate as shown in Figure 4(a). The dual-channel pyroelectric detector has two channels functioning as detection channel and reference channel and both contain compensation elements to counter ambient temperature changes and mechanical vibrations (as shown in Figure 4(b)).

Tan *et al.* [29] demonstrated sensing of eight different toxic gases (H_2S, CH_4, CO_2, CO, NO, CH_2O, NO_2, and SO) by integrating plasmonic metamaterial absorbers with the pyroelectric detectors at the pixel level. The absorption filter is metal (gold)-insulator (SiO_2)-metal (gold) structure-based metamaterials which is fabricated directly on top of the lithium tantalate pyroelectric substrate. The limit of detection of the sensor for various analytes can be improved by reducing the thickness of lithium tantalate film. Since the spectral response of the detector and gas absorption lines are overlapped, another way to enhance the LOD of the device could be via improvement of the quality factor of the metal-insulator-metal based absorber.

Zhang *et al.* [30] used dual-wavelength pyroelectric detector to detect ethylene (C_2H_4) gas in the concentration range of 1 – 100 ppm. It is to be noted here that ethylene is a colorless and odorless gas which has absorption peaks at 3.56 μm, 6.8 μm, and at 10.54 μm which is also the strongest one. They also used a lock-in amplifier to remove noise from the output signal. Kindly note that this amplifier is built of a bandpass filter, a low pass filter, and a phase-sensitive detector with the help of which it converts the output from pyroelectric detector into a measurable DC voltage.

3) Photodiode: The NDIR gas sensor with a photodiode-based detector has been explored in the literature. Fleming *et al.* [31] developed an MBE-grown pentanary alloy (AlGaInAsSb) based IR-emitter (LED)/IR-detector (photodiode) system for CO_2 detection. The power consumption by this pair is only 35 mW as compared to high power consumption in other emitter/detector combinations where hundreds of milli-watt power are required. They also demonstrated that by using multilayer thin-film optical interference bandpass filters, the cross-talk with neighboring gases like N_2O can be reduced/eliminated. Nakayama *et al.* [32] developed an AlInSb photodiode by molecular beam epitaxy (MBE) on a GaAs (100) semi-insulating substrate for methane (3.3 μm) detection. They inserted optimized dislocation filter layers (DFL) in the buffer layer itself which helped in reducing the threading dislocation density in the active layer. Generally, photodiodes are used in detection where IR LED emitters are employed, however, there are reports where photodiodes are employed for MEMS IR emitters as well. Barritault *et al.* developed an NDIR CO_2 gas sensor based on MEMS-based micro hotplate as an IR source and an optically immersed photodiode was used as an IR detector. The photocurrent was measured in photovoltaic mode i.e. no bias voltage was applied during measurement and it was found to be of the order of 0.07 μA, however, an error of the order of $\pm 0.02 \mu A$ is inherited due to poor stability of the photodiode. To relate this photocurrent measurement to optical power received by the photodiode, they measured the current-sensitivity at a wavelength of 4.26 μm using a separate blackbody emitter.

The advantage of photodiodes is their ability to operate without additional reference voltage and hence, stabilization of the output voltage is easier. It also helps in reducing the overall power consumption in the device.

4) Bolometer: Generally, bolometers are capable of detecting IR wavelengths of the order of 8 μm – 12 μm. Therefore, it is as such not very efficient in gas sensors like CO_2 detectors since it requires detection in a range much below this optimal wavelength. In such cases, different arrangements have to be done.

Barritault *et al.* [33] demonstrated a MEMS IR source-based low power CO_2 gas sensor utilizing an array of amorphous silicon (as a thermometer layer) uncooled micro-bolometer. Every bolometer possesses an absorbing layer as a membrane supported on the substrate via arms and pillars. To utilize a micro-bolometer as a detector in the NDIR sensor, the cavity between this membrane and substrate is tuned to a quarter wavelength resonant cavity. The smooth operation of the bolometer needs a vacuum level of 10^{-3} mbar. Therefore, the detector needs to be kept in a small vacuum chamber which needs to be pumped continuously. Nakayama *et al.* [32] designed and developed an NDIR CO_2 gas sensor where they used Fabry-Perot based bolometer combined with glass plate infrared filter. This structure was very helpful in diminishing the crosstalk effect of H_2 vapor which otherwise dominates in NDIR sensors where non-symmetric Fabry–Perot IR-absorbing structures are employed as the detector.

C. Based on Cell Topology

The gas cell in an NDIR gas sensor has three-fold objectives which are: to provide a confine path for emitted infrared radiation to reach the detector without getting influenced by the external environment factors, construct a confined regime for target gas interaction, and provide a support structure to the overall gas sensing system.

Apart from these conventional gas cells, a number of designs have been proposed in the literature. Mayrwöger *et al.* [34] used ZEMAX software to understand the effect of gas cell design on sensing properties. The three cell designs they used were internally reflective tube, internally reflective ellipsoid, and a spiral design within a cylinder. It was found that the spiral geometry of the cell helps in achieving greater optical length which directly relates to sensitivity enhancement of the device.

1) Face-to-Face: This is the most common type of gas cell where the IR emitter-detector is arranged in front of each other in a tubular channel kind of configuration.

Miyazaki *et al.* [35] developed a face-to-face NDIR CO_2 gas sensor where a dual-band metasurface thermal emitter was used as IR source, and a dual-channel pyroelectric device was utilized as an IR detector. The polarization and angle independent metasurface based on patterned $Au/Al_2O_3/Au$ structure, emitted radiation at two separate wavelengths i.e. 4.26 μm and 3.95 μm. The mid-IR rays of the former wavelength can be absorbed by the CO_2 molecule while the later wavelength light acted as a reference signal. The required power reduction achieved with this thermal emitter was $\sim$30% as compared to a conventional blackbody emitter. Wong and Schell [4] demonstrated a zero-drift gas sensor based on face-to-face gas cell arrangement where one IR emitter and dual-channel detectors (signal and reference channels) are used. They used the fact that if the spectral content of IR light can be kept same, then the output of the device remains constant which is represented as a ratio of signal to reference output. To introduce a difference in output from signal and reference channels, an absorption bias is introduced by using different channel lengths for the two. In fact, they kept the chamber length for the signal longer than the reference channel and hence the alteration of the ratio of these signals suggests the presence of analyte qualitatively and quantitatively. Sklorz *et al.* [36] developed an ethylene gas sensor with conical-shaped gas cells equipped with Fresnel lenses. The IR emitter and detector are placed face-to-face and with this configuration, they could achieve the lowest detection limit of 34 ppmv for this gas without using costly lock-in amplifier while it improves to 25 ppmv with the incorporation of this amplifier. Apart from the basic metallic gas cells, Peng *et al.* [37] used mid-IR hollow fiber as a gas cell since its optimum transmission band overlaps carbon dioxide's absorption spectrum, and hence it can act as a filter. The device was found to be more sensitive as compared to metallic gas cells with the sensitivity of 1.82mv/ppm. Shah et.al demonstrated a face-to-face IR emitter- IR detector configuration of NDIR gas sensor for monitoring toxic gases like CO and CO_2 inside the crew cabin of manned space shuttles.

2) Planar: In a practical approach, Tan *et al.* developed a three gas (methane, carbon dioxide and carbon monoxide) detection system by utilizing four single-channel pyroelectric detectors (three for the analytes and one for reference) [38]. To improve the optical path length, they designed a gas chamber (made up of top plane, bottom plane, and a curved wall) in such a way that the infrared light is reflected twice before detection. The size of the gas chamber is 10 mm (radius) $\times$ 10 mm (height) and its shape resembles two crossed elliptical surfaces. Wittstock *et al.* [39] designed and developed a planar gas sensor to monitor lower explosion limit of methane. They used a planar structure with dual photoacoustic detectors. The LED (used as IR source), is positioned at the focal points of the two half-ellipsoids by which optical paths of 25 mm and 20 mm, respectively could be achieved. By utilizing such a structure, drifts in the light intensity of the IR source have been nullified. Fleming *et al.* [31] developed a planar NDIR CO_2 structure based on MBE grown pentanary alloy (AlGaInAsSb) based IR emitter and detector to improve cross sensitivity.

3) Cavity: In designing an NDIR sensor with a cavity, number of reflections inside the cavity is very important along with the optical path since with the reflections, the energy of the infrared signal decreases.

Jing *et al.* [40] designed MEMS cavity-based gas cell with good transmissivity with the help of Ansys workbench, and Tracepro software. They also demonstrated the fabrication of chambers of size 10 mm $\times$ 10 mm $\times$ 1 mm on a 6-inch wafer via etching square cavity on the front window and through-hole window from the backside. Han *et al.* [41] proposed a tapered optical cavity with a stair like structure inside it as an IR ray condenser for accurate detection of CO_2 gas. The advantage of using a stair-tapered reflector optical cavity is that it decreases the number of reflections in the path while maintaining a constant angle of incidence. NDIR sensor employing this type of cavity is also less sensitive towards ambient temperature fluctuations than the conventional gas sensing structure.

There are reports where two cavity structures are also proposed. Yi *et al.* [42] used such a structure to design a NDIR CO_2 sensor where the first cavity was utilized to ensuring the proper focusing at the detector side, while the second one was used to provide larger path length through cavity.

They achieved an amplification gain of about $\sim$18000 with such a structure for detection of CO_2 gas in the concentration range of 0-2000 ppm. Figure 5 summarizes the various gas cells discussed above. Apart from these conventional cell topology, recently, NDIR gas sensors have been developed with a chamberless approach by incorporating parabolic reflector in the light source [43]. When the light source is kept at the focal point of a parabolic reflector, the light beam is

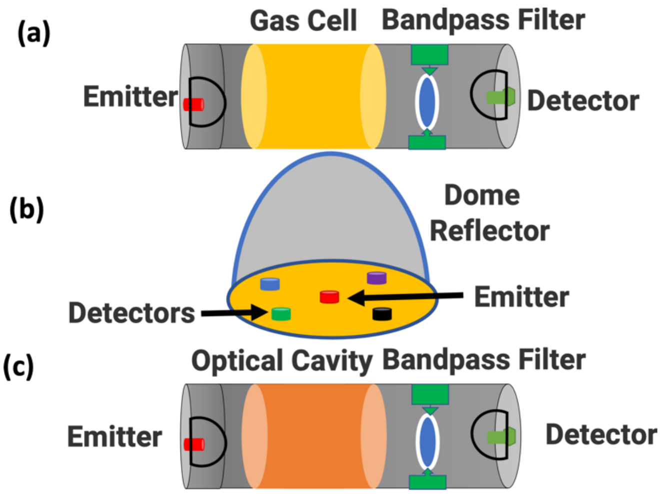

Fig. 5. (a) Face-to-face cell topology where emitter and detector are vis-à-vis (b) in a planar topology, emitter and detector is placed in a planar configuration and (c) an optical cavity is placed in the optical path in cavity-based topology to enhance optical path.

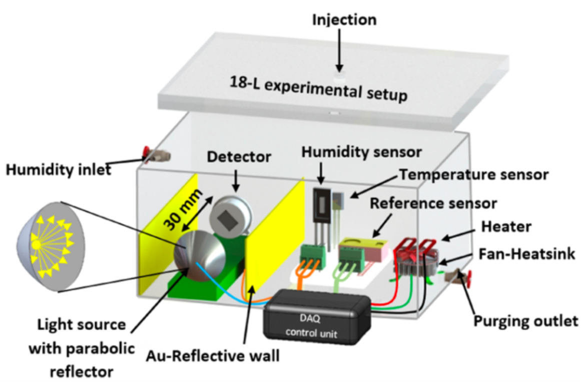

Fig. 6. Experimental set-up for chamberless CO_2 gas sensor adapted from [44].

propagated along the beam axis without or with negligible spherical aberration. Vafaei and Amini [44] developed such an NDIR carbon dioxide sensor as shown in Figure 6 below. As evident from the figure, the embedded parabolic reflector doesn't allow any dispersion and a collimated light is detected by a thermopile detector (HIS A22 F4.26/180, Heimann Sensor GmbH). Due to the linearity in the response of the device, they were also able to compensate for drift and fluctuations associated with ambient temperature, humidity, and analyte concentration.

To enhance the accuracy of NDIR sensors, the interaction between IR rays and gas molecules should be longer which in turn, make the device heavier. Therefore, some groups have proposed waveguide-based gas sensors. Consani *et al.* [45] developed an NDIR CO_2 gas sensor based on evanescent-field sensing by confining the electromagnetic field in a silicon waveguide which has a size comparable to the wavelength. Actually, in a sub-wavelength dielectric waveguide, a good amount of electromagnetic field leaks out to cladding from the core of the waveguide and hence, can be used in gas sensing. The emitted IR light was butt-coupled into the waveguide, and a grating coupler (etched at the other side of the polysilicon slab) was used to outcouple it. Yazici *et al.* [46] used flip-flop

TABLE I
CLASSIFICATION OF NDIR GAS SENSOR

Based on Components	Remarks	Reference
[a]Lamps	simple, cost-effective, high spectral emission, bulky, consume more power	[10]
[a]MEMS Heater	energy efficient, reliable, small response time, less thermal mass, capability of miniaturization, CMOS- compatible	[15]
[a]LED	considered as safe IR source, low response time, high signal-to-noise ratio, no temperature stabilization problem	[21]
[b]Thermopile	cost-effective, consumes less power while affecting the efficiency, high noise levels in the output	[23]
[b]Pyroelectric	cost-effective, better resolution particularly, for spectrum beyond 7 µm, no active cooling system required for room temperature operation	[26]
[b]Photodiode	able to operate without additional reference voltage, easy stabilization of the output voltage, low power consumption	[31]
[b]Bolometer	effective only in 8 µm – 12 µm wavelength range, not useful for several critical gases like CO_2	[33]
[c]Face-to-face	IR emitter-detector is arranged in front of each other, simplest arrangement, multi-channel detectors can be accommodated	[35]
[c]Planar	improved optical path length, multi-analyte detection is possible, miniaturization possible, improved cross-sensitivity	[38]
[c]Cavity	increased optical path, less affected by ambient conditions	[41]

[a]Based on infrared Source; [b]Based on infrared detector; and [c]Based on cell topology

technology to integrate thermopile detector with a mid-IR waveguide to detect N_2O gas, which has an absorption at 3.9 μm. The gas-IR rays' interaction is governed by the length of the waveguide and an SNR of as high as 4700 and 3500 have been recorded at 15Hz chopping frequency which translates to 1800 and 2000 pp resolution for short and long spiral waveguides. Table I summarizes the classification of gas sensors as detailed in this section.

IV. CURRENT TECHNOLOGY

The NDIR sensors suffer from several issues such as selectivity (due to interfering nearby gases), sensitivity (because of small output signal due to weak absorption of gases), and high cost (due to highly sophisticated optical components). In this regard, optical filters used in these sensors play a vital role in defining the aforementioned sensor characteristics. Therefore, the design, fabrication, and utilization of a correct optical filter are very important. Several bandpass fitters have been proposed in the literature for effective gas sensing using the NDIR technique. Maza *et al.* [47] demonstrated both theoretically as well as experimentally that a macroporous silicon photonic crystal with a cavity in the middle can be used as a narrow bandpass optical filter in detection of CO_2 gas. The silicon photonic crystal-based filter was tested for its optical robustness and their selectivity. It was found that due to the high-quality factor of the filter, even two gases whose spectrum overlaps can be distinguished. Therefore, these filters have the capability of cutting the cost of the NDIR gas sensor at the same time enhances the gas selectivity by reducing the spectral interference issue.

Diharaja *et al.* [48] used a filter based on the principle of interferometry which has a bandpass of $\sim$4.63 μm in the development of their NDIR carbon-monoxide gas sensor. This interferometric optical filter helps in achieving the NDIR CO sensor sensitivity of as high as 7 mV/ppm. Fleming *et al.* [31] developed a Ge/Nb_2O_5 multilayer-based bandpass filter for improving/eliminating cross-talk of N_2O gas in an NDIR CO_2 gas sensor. The material combination for the filter was chosen based on its high degree of optical transparency in the targeted mid-IR regime. Another important advantage of using the multilayer arrangement of Ge and Nb_2O_5 is the low spectral shift angles provided by it. It should be noted here that the spectral shifts of incidence light from the normal become very important (particularly for improving the SNR) for applications where the IR emission extends to higher angles. Dinh *et al.* [49] developed a two-cavity bandpass filter using germanium substrate and SiO coating for selective detection of ammonia gas in the concentration range of 1 ppmv – 20 ppmv. The central wavelength (CWL) of the designed filter was 10.39 μm with half and the full bandwidth of 190 nm and 1068 nm respectively. Although, there are three low-interfering bands (9.61-9.70 μm, 9.92-9.93 μm, and 10.29 – 10.49 μm) for ammonia but 10.29 μm-10.49 μm range was targeted for two reasons. First, the other bands were very narrow, and designing and fabricating filters or those ranges would be really a tedious job with current manufacturing technology. The other important factor supporting this targeted range is that the moisture has minimal interference in this spectral range. There have been other measures also taken by various research groups to improve the performance parameters at a reduced cost.

In such an attempt, Kim *et al.* used a hydrophobic film of Parylene-C film (0.5 μm thick) on the reflector surface of White-cell structured NDIR sensor which enhance the sensitivity, and accuracy of the device [50]. It should be noted here that White cell is commonly used to produce multi-pathway gas channels for NDIR sensor [51]. There has been significant work on reducing the overall cost of the device as well. Mayrwöger *et al.* [52] used two non-symmetry Fabry- Perot absorber structures (FPAS) as IR emitter and detector. The device consists of a dielectric layer sandwiched between two metal mirror layers where selectivity to particular gas depends upon the thickness of the dielectric layer where it has to be $(2n + 1)\,\lambda_d/4$ where n is the order of absorption peak and λ_d is the wavelength in the dielectric layer. The actual absorption of IR takes place in the top metal mirror while the bottom metal mirror which is thicker than the former and acts as an IR reflector. In another work, Akram and Nikfarjam reduced the overall cost of the NDIR device by choosing low-cost polymers for fabricating costly parts particularly, gas cells and optical windows [53]. They used a hundred-nanometer gold-coated PMMA channel due to reasonably good reflectivity and durability of this polymer in the mid IR range. Similarly, they successfully demonstrated PDMS as an optical window which helped in decreasing overall cost.

Miniaturization of the NDIR sensor has also remained a problem over the time. However, a unique solution has been proposed by Ayerden et. al who proposed a methane sensor where the resonator cavity of a MEMS linear -variable optical filter was used as a gas cell [54]. They used highly reflective Bragg mirrors to achieve multiple reflections which increased the effective path length by 62.2 folds. Integration of metamaterials into emitter and detector has also been found advantageous in reducing the size of the optical chamber. Lochbaum *et al.* [55] achieved a 30-fold reduction in size by integrating metamaterials into both emitter and detector as on-chip optical filters.

Interference of the gases which have their absorption spectrum nearby to the target analyte is also a major concern. Dinh *et al.* [56] suggested a double bandpass filter instead of a gas filter correlation (GFC) to improve the selectivity of an NDIR nitric oxide sensor. It should be noted that GFC is usually used in NDIR based NO sensors to compensate for interfering gases such as CO, CO_2, SO_2, and H_2O. Unfortunately, the use of such a double bandpass filter hits the sensitivity very badly which also affects the lowest limit of detection.

New approaches for developing NDIR sensors via combing with other sensing principles have also been found advantageous. Moumen *et al.* [57] combined the NDIR gas sensing technique with chemical sensing by integrating CO_2 sensitive sorption layer in the gas cell so that a preconcentrated gas can be monitored. They combined polyethyleneimine cross-linked with glutaraldehyde as CO_2 sorption material on the surface of which CO_2 is adsorbed and diffused into the bulk and can thus can be monitored. This helps in the miniaturization of the device by not imposing longer path length requirements. Graf *et al.* [58] also combined chemical sensing with NDIR detection and renamed their sensing technique as adaptable non dispersive infrared (ANDIR) gas sensor. With this approach, the flexibility of NDIR is enhanced which have great impact on the sensors' cost. This is particularly due to the incorporation of broadband optical filters in place of narrowband filters. The obtained data were analyzed with support vector machine pattern recognition algorithm.

V. Conclusion

NDIR gas sensors are very crucial for industrial applications and even though, the technology is matured, the issues like lower detection limit, and interference with humidity and other gas molecules need to be addressed. In this review article, we have seen that these shortcomings can be addressed by selecting IR source, detector, and bandpass filter dexterously. Apart from these, the design and implementation of gas cells also affect these parameters, and hence, this has also been reviewed in this article. There has been reports on unconventional techniques to improve NDIR sensors' properties and hence, it has been also discussed to enable researchers working in the domain to get familiarized with the current trend.

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Ravindra Kumar Jha (Senior Member, IEEE) received the Ph.D. degree in nanotechnology from the Indian Institute of Technology, Kharagpur, India, in 2017. He joined the Centre of Nano Science and Engineering (CeNSE), Indian Institute of Science (IISc), Bengaluru, India, in 2018, where he worked as a Postdoctoral Fellow for more than two years. He served the Council for Scientific and Industrial Research (CSIR), India, as a Scientist for more than a year before moving to the Indian Institute of Technology, Guwahati, India, where he is an Assistant Professor with the Department of Electronics and Electrical Engineering. His research interests include synthesis and characterization of electronic materials for sensing applications, development of gas sensors based on various transduction techniques, and interface electronic circuits for gas sensors.