ABSTRACT In this paper, we propose a method to simultaneously measure carbon dioxide (CO$_2$) concentrations and ultrasonic vibration using fiber sensors with a tunable fiber ring laser based on a loop design. The in-line interferometric vibration sensor consists of a single-mode-multimode-single-mode fiber structure and detects continuous dynamic vibrations through intensity demodulation. The evanescent wave absorption based CO$_2$ sensor is composed of a no-core fiber coated with silica derived from tetraethylorthosilicate. The fiber ring laser output is tuned to the CO$_2$ absorption wavelength of 1574.6 nm, which also best matches the quadrature bias point of the vibration sensor. The vibration frequency signals from 10 Hz to 50 kHz, and fast detection of CO$_2$ concentrations from 10% to 100% are experimentally demonstrated. The proposed hybrid sensor system is a promising method for monitoring the gas pipelines operating state, gas turbines, nuclear power plants, and automotive engines, where both vibration and CO$_2$ concentration measurements are essential.

INDEX TERMS Vibration sensing, carbon dioxide sensing, fiber optic sensors, tunable fiber ring laser.

I. INTRODUCTION Monitoring and quantifying the vibrations of critical infrastructures is essential for early damage detection, structural safety, and maintenance improvement. Conventional vibration monitoring based on piezoelectric accelerometers [1], inductive [2], and capacitive [3] are incompatible for harsh environmental conditions and suffer from electromagnetic interference. For several decades, fiber optic sensors have been gaining attention, due to their small size, immunity to electromagnetic interference, light weight, ease of installation, and corrosion resistance [4]. Various fiber optic-based vibration sensors, including the fiber Bragg grating (FBG) [5], the Mach–Zehnder interferometer (MZI) [6], and the Fabry-Perot interferometer (FPI) [7] have been widely investigated. In 2013 Wu et al. [8], Han et al. [9] demonstrated a vibration sensor based on a fiber ring laser with an FBG and a tunable optical band-pass filter. In 2014, Liu et al. [10], investigated an ultrasonic vibration sensor using a fiber ring laser with two FBGs placed at the same sensing location and with different spectral responses to external vibrations. Hence, the external vibrations influenced relative spectral shifts of the FBGs and modulated to fiber ring laser cavity loss. However, the lasing wavelength of the FBG-based vibration sensors would be on the slope of the FBG reflection spectrum, which requires additional high-resolution tunable filters. Also, the fabrication of FBG sensors requires expensive equipment, such as an excimer laser, which results in a relatively high cost for these types of sensors. The most attractive technique is multimode interference in a single-mode-multimode-single-mode (SMS) fiber structure [11], [12]. The SMS fiber structure has advantages of simple implementation, low manufacturing cost, high sensitivity, and easy fabrication. As a result, research into the SMS fiber structure is attracting wide interest. SMS fiber sensors employ the multimode interference principle and have been intensively investigated to measure strain, temperature, refractive index, and pressure with high sensitivity [13].

On the other hand, accurate monitoring of carbon dioxide (CO$_2$) concentration is essential to predicting environmental impacts and production leakages in gas pipelines. CO$_2$ is considered a primary greenhouse gas and contributor to...
global warming, and also the main cause of corrosion in natural gas pipelines [14]. Gas detection based on fiber optic sensors is a promising method due to their high sensitivity and corrosion resistance. Evanescent wave absorption-based fiber optic sensors are used in a broad range of applications, from gas sensing to biosensing. The optical evanescent wave interacts with the CO$_2$ gas molecules and the concentrations can be determined by measuring the degree of absorption of transmitted light directed through a fiber sensor with a response time on the order of seconds [15].

Acoustic vibrations and CO$_2$ gas emissions are two primary monitoring parameters in gas turbine plants, airplane engine turbines, and oil/gas pipelines [16], [17]. Current techniques for monitoring vibration and CO$_2$ gas leakage in such critical structures involve expensive and complex sensors. Simultaneous monitoring of both vibration and CO$_2$ requires a novel hybrid sensor system that allows highly sensitive and cost-effective evaluation of structural health and gas leakage concentration. In this paper, we proposed simultaneous ultrasonic vibration and CO$_2$ sensing, where both sensors utilize the same tunable fiber ring laser source. The two fiber sensor structures include (i) a simple SMS fiber structure for vibration sensing and (ii) evanescent wave absorption based on a no-core fiber coated with silica for CO$_2$ measurement. Both the sensor structures use the narrow-linewidth tunable fiber ring laser, where the lasing wavelength is tuned to the CO$_2$ absorption wavelength of 1574.6 nm by varying the displacement of a tied loop structure into the laser cavity. The main objective of this research study is to monitor oil/gas pipelines and gas wells, where vibration and CO$_2$ leakage are two critical parameters for safety and maintenance. To the best of our knowledge, this is the first demonstration of monitoring both vibration and CO$_2$ simultaneously, while both the sensors share a single tunable fiber ring laser source.

FIGURE 1. Schematic representation of tunable fiber ring laser.

II. OPERATING PRINCIPLE

A. TUNABLE FIBER RING LASER

The schematic representation of the tunable fiber ring laser is illustrated in Figure 1. The ring laser comprises 10 meters of erbium-doped fiber (EDF), 980/1550 nm wavelength division multiplexer (WDM), and 980 nm pump laser. Pumping the EDF by a 980 nm laser will cause stimulated emission [9]. By creating a simple tied fiber loop into the ring cavity and applying strains on the fiber loop, one can realize tunable spectral wavelength output. As shown in Figure 1, when the light entered the fiber loop, the light partly leaked into cladding modes and then coupled back. Fixing one end of the fiber loop while moving the other end using a linear translation stage will cause the loop diameter to change. Therefore, the ring laser’s resonance peak wavelength changes linearly with the applied displacements. In 2016, Z. Lui et al. [18], demonstrated a displacement sensor based on a fiber ring laser. The designed a small knot in the form of a fiber loop using a piece of SMF, which acts as both the sensing head and the filter. The sensing head consists of standard SMF without removing the coating, hence it has high mechanical strength and can apply large displacements. The displacement can be applied to the macro fiber loop by moving one side of the linear translation stage, which will cause the spectrum to change linearly with a sensitivity of 227.5 pm/mm. The relation between the lasing wavelength and fiber loop radius of curvature is described as [18],

$$\frac{d\lambda}{dR} = \frac{\lambda}{R + x}$$

where $\lambda$ is the peak wavelength, $R$ is the curvature radius of the fiber loop, and $x$ is the distance from the fiber cross-section center. Changing the curvature radius of the fiber loop appropriately will change the wavelength of the ring laser output spectrum. Since the lasing wavelength depends on the loop curvature radius, one can fix the loop radius to a desired wavelength. Specifically, by tuning the displacements on the fiber loop, the ring laser wavelength can be tuned to a CO$_2$ absorption wavelength of 1574.6 nm.

B. SMS FIBER STRUCTURE BASED VIBRATION SENSOR

A schematic representation of the SMS fiber structure is shown in Figure 2(a), where an MMF is sandwiched between two SMFs. At the lead-in interface, where light is injected.
from SMF-1 into the MMF section, multiple modes will be excited and then propagate with interference along the MMF section with their corresponding propagation constants. At the lead-out interface, the multiple modes couple back into the SMF-2. The output power at the lead-out SMF is determined by the mode interference between the various modes in the MMF and the coupling between the MMF and lead-out SMF, which is significantly dependent on the physical properties of the MMF section.

For the lead-in SMF, the fundamental mode field distribution is assumed to be $E(r, 0)$. When light is transmitted into the MMF, the input net field decomposes into the linearly polarized Eigenmodes $L_{P_{nm}}$ of the MMF [19]. Assuming the axes of the lead-in SMF and MMF are perfectly aligned, only the $L_{P_{0m}}$ modes can be excited within the MMF section. Assuming the field profile of $L_{P_{0m}}$ as $P_{m}(r)$, the field distribution can be expressed as [11],

$$E(r, 0) = \sum_{m=1}^{M} c_m P_m(r)$$

where $c_m$ is the exciting coefficient of each Eigenmode and $M$ is the total number of modes within the MMF section. The exciting coefficient between the fundamental mode within SMF and the $M^{th}$ order mode within the MMF can be expressed as [12],

$$c_m = \frac{\int_{0}^{\infty} E(r, 0) P_m(r) rdr}{\int_{0}^{\infty} P_m(r) P_m(r) rdr}$$

In practice, the lead-out SMF normally has the same optical parameters as those of the lead-in SMF. Therefore, the output optical power at the lead-out SMF can be calculated using [20], [21],

$$L_s(z) = 10 \log_{10} \left( \sum_{m=1}^{M} c_m^2 \exp(i\beta_m z) \right)^2$$

where $z$ is the length of the MMF section. If a vibration is applied to the MMF section, the length, $z$ will change, thereby altering the output intensity. When the MMF fiber is wrapped around the piezoelectric cylinder and vibrates, the fiber experiences tensile and compressive strains. As a result, the transmission spectrum will periodically change to blue-shift or red-shift. At a certain vibration frequency, the resultant spectrum intensity increases or decreases. A sinusoidal-based waveform variation exists in which a linear intensity response can be observed at a quadrature bias point. Figure 2(b) illustrates a vibration sensing based on an intensity modulation method. Although a superimposed interferometric spectrum will be observed as a result of multimode interference, the spectral shift from all the in-line interferometers is still expected to be linear.

III. EXPERIMENTAL SETUP AND RESULTS

Figure 3 illustrates the experimental setup of ultrasonic vibration and CO$_2$ sensing based on a tunable fiber ring laser source. A 10 m EDF fiber acts as an active gain medium, which is pumped by a 980 nm laser diode through a 980/1550nm WDM coupler. Thereafter, the stimulated signal passes through an isolator and polarization controller (PC). The isolator is employed to make sure the lasing only follows one direction around the fiber loop, and the PC is used to adjust the light polarization before it’s sent to the tied fiber loop. A simple knot fiber loop structure is positioned on a solid aluminum breadboard plate, and the lead-in/lead-out fibers are fixed on a translation stage. An optical spectrum analyzer (OSA) is used to measure the ring laser’s output spectrum.

The measured peak wavelength is 1574.81 nm with a high signal-to-noise ratio (SNR) of $\sim$48 dB when the loop diameter is fixed at 31 mm and 980 nm pump laser power is 280 mW. Changing the displacement of the fiber loop structure precisely, the measured optical spectrums shown in Figure 4. To obtain a CO$_2$ absorption wavelength of 1574.6 nm, the displacement changed to 800 $\mu$e using
a translation stage. The stability of the ring laser wavelength and output power is evaluated over a period of 120 min and shown in Figure 5. The laser has a low wavelength drift of 0.026 nm, and the power fluctuations are <1.8%. The ring laser output signal is sent to both the vibration and CO₂ sensors using a 50/50 3 dB coupler. The ring laser output power can be optimized by changing the power of the 980 nm pump laser. The experimental setup of the vibration sensor based on a SMS fiber structure is illustrated in Figure 3 (blue dashed line). Figure 6 shows the measured transmission spectrum of the SMS fiber structure output based on a broadband laser source with a central wavelength of 1550 nm (Thorlabs, S5FC1550S). The interference spectrum has several peaks and dips due to a superposition of multiple mode interferences. The spatial frequency spectrum can be obtained for the SMS fiber transmission spectrum using fast Fourier transform (FFT). The spatial frequency ($\xi$) can be expressed as $\xi = \Delta m_{\text{eff}} L/\lambda_0$, where $\Delta m_{\text{eff}}$ is the differential modal group index, $L$ is the interferometer length, and $\lambda_0$ is the center wavelength [22], [23]. The CO₂ absorption wavelength of 1574.6 nm is also a best bias point on the measured spectral slope, shown as a red dot in Figure 6 inset. It is important to mention that because the CO₂ absorption wavelength (1574.6 nm) is around the quadrature bias wavelength. The operating wavelength works best for the vibration sensor with an appropriate SNR of the measured frequency spectrums.

To demonstrate ultrasonic vibration sensing using a tunable fiber ring laser based on SMS fiber structure, a 16 cm MMF (total length of MMF is 22 cm, and the core diameter is 62.5 µm) wrapped and glued around the piezoelectric transducer (PZT, outer diameter: 32 mm), where the PZT is driven by a waveform amplifier (Accel instruments, TS250) and an arbitrary waveform generator. The sinusoidal signal with a fixed peak-to-peak amplitude of 5 Vpp and various sinusoidal vibration frequency signals are applied to the PZT. The intensity-modulated signal is detected by a low-noise photodetector (Wiserlabs, PD450MA) and analyzed by an oscilloscope (Teledyne LeCroy, WaveSurfer 3000z). The measured frequency spectrum using FFT has a very good SNR of 41 dB at a 500 Hz frequency signal, as shown in Figure 7(f). To demonstrate the capability of detecting various vibration frequency signals using the proposed hybrid sensing system, frequencies from 1 to 50 kHz (limited by the cut-off frequency of the PZT voltage driver) are measured and illustrated in Figure 8. The measured SNR for vibration frequency signals from 10 Hz to 50 kHz is illustrated in Figure 9. The measured frequency, as a function of the applied input vibrational frequency is shown in Figure 9 inset. The measured SNR range from 9.8 dB to 56 dB is observed over a broad range of vibration frequencies (10 Hz to 50 kHz) and able to accurately monitor the external vibration disturbances.

The experimental setup of a CO₂ sensor is illustrated by the red dashed line in Figure 3. A 15 cm no-core fiber is spliced between two single-mode fibers. The no-core fiber exhibits enhanced evanescent wave interaction with the surrounding environment and offers a more sensitive response than the traditional MMF. A sol-gel dip-coating method was used to immobilize the silica coating on the no-core fiber. The no-core fiber section was pulled at a rate of ~1 cm·s⁻¹ through the tetraethoxysilane (TEOS) based precursor.
(mixture of 4.5 ml TEOS, 4.5 ml ethanol, and 1.0 ml 1.0 M HCl, rigorously stirred for 1 hour at \(\sim 50 \, ^\circ C\)). Then the coated no-core fiber was calcinated at 600 \(^\circ C\) for 1 hour to ensure the conversion of TEOS to silica. TEOS derived silica is chosen for CO\(_2\) sensing because it demonstrated high adsorption selectivity of CO\(_2\) and similar refractive index (RI) compared with the fiber core. Also, the long-term stability of silica material makes it possible for practical applications [24]. Figure 10 shows scanning electron microscopy (SEM) images of the coated no-core fiber. The thickness of the immobilized SiO\(_2\) layer is \(\sim 600 \, \text{nm}\) and the dip-coating procedure provides an even coating on the coreless fiber, as shown in Figure 10. The low refractive index silica material has improved gas absorption, based on the evanescent wave theory [25]. The coated no-core fiber is placed into the gas chamber, and the transmittance signal is then measured by an optical power meter using a ring laser operating.
at a CO₂ absorption wavelength of 1574.6 nm. CO₂ with different concentrations are exposed to the sensor with a reference background gas of N₂ and transmission power measured consequently. The measured transmittance toward different CO₂ concentrations is illustrated in Figure 11(a). With decreasing CO₂ concentrations from 100% to 10%, the CO₂ sensor showed reduced transmittance and the minimum detection limit in this experiment is 10%. The proposed sensor shows good repeatability, as demonstrated with 100% CO₂ cycles, and illustrated in Figure 11(a) inset. Moreover, due to the physisorption-based mechanism, the transmittance data showed full reversibility and a linear relation corresponding to various CO₂ concentrations. The calculated response and recovery time of the sensor are 31 and 52 seconds, respectively, as shown in Figure 11(b). It is important to mention that the intrinsic response time can be anticipated much shorter with a smaller gas reactor tube. However, in the experiments we used only availability of large diameter gas reactor tube (2 cm in radius with 30 cm in length), therefore the adsorption of gases takes relatively higher time to reach the equilibrium [26].

The silica-coated no-core fiber based CO₂ sensor has good sensitivity and repeatability. Moreover, the proposed vibration sensor can detect a wide range of vibration frequencies (10 Hz to 50 kHz) with a high SNR (41 dB at 500 Hz vibration signal). Table 1 compares the other fiber optic vibration sensing techniques with the proposed method. The other recent developments, such as fiber loop mirror interferometer [25], in which the maximum detectable vibration frequency up to 1.2 kHz, in [26], a vibration sensing with FBG with a frequency range of 50 to 200 Hz, and in [27], demonstrated a liquid-filled photonic crystal fiber for a frequency range of 10 Hz to 20 kHz with an SNR of 33 dB (at 600 Hz vibration signal).

In 2019, J. Gerguis et al. [32], demonstrated a CO₂ sensing based on a swept fiber laser source using a micro-electromechanical system (MEMS) tunable filter, a semiconductor optical amplifier as gain medium and a fiber ring. The effects of pump current, tuning speed, and the tuning direction on the transmission spectrum in the presence of CO₂ gas was demonstrated. In 2019, A. Othman et al. [33], proposed a mode-locked fiber ring laser using a non-zero dispersion-shifted fiber to enfold the CO₂ absorption wavelengths of 1574 and 1605 nm. However, the proposed sensor system has a benefit of high wavelength and power stability, simultaneous monitoring of CO₂ and vibrations, where both vibration and CO₂ concentration measurements are essential in practical applications.

IV. CONCLUSION

We demonstrated simultaneous monitoring of ultrasonic vibrations and CO₂ concentration based on a tunable fiber ring laser. The vibration sensor consists of a simple, low-cost single-mode-multimode-single-mode (SMS) fiber structure. Whereas, the CO₂ sensor comprises of an evanescent based no-core fiber coated with tetrathoxysilane (TEOS) derived silica. Both sensors share the same tunable ring laser source and the ring laser output wavelength is tuned to the CO₂ absorption wavelength. The ring laser wavelength tuning is determined based on strain applied on the tied loop structure into the laser cavity. To obtain the best SNR, the tuned CO₂ absorption wavelength of 1574.6 nm also matched the
quadrature bias point of the SMS spectral slope. The vibration frequency signals from 10 Hz to 50 kHz and CO$_2$ concentration from 10% to 100% are successfully demonstrated. The measured CO$_2$ response time and recovery time of the sensor are as low as 31 s and 52 s, respectively. The experimental results indicate that the proposed sensor system is a promising method for monitoring oil and gas pipelines, nuclear power plants, and automotive engines, where simultaneous monitoring of vibration and CO$_2$ leakage is crucial.

ACKNOWLEDGMENT

This technical effort was performed in support of the National Energy Technology Laboratory’s ongoing research under Natural Gas Infrastructure FWP and SubTER projects.

REFERENCES

[1] F. A. Levinzon, “Fundamental noise limit of piezoelectric accelerometer,” IEEE Sensors J., vol. 4, no. 1, pp. 108–111, Feb. 2004.
[2] L. Liu, L. Chen, S. Wang, Y. Yin, D. Liu, S. Wu, Z. Liu, and X. Pan, “Improving sensitivity of a micro inductive sensor for wear debris detection with magnetic powder surrounded,” Micromachines, vol. 10, no. 7, p. 440, Jul. 2019.
[3] F. Büsching, U. Kulau, M. Gietzelt, and L. Wolf, “Comparison and validation of capacitive accelerometers for health care applications,” Comput. Methods Programs Biomed., vol. 106, no. 2, pp. 79–88, May 2012.
[4] P. Lu, N. Lalami, M. Badar, B. Liu, B. T. Chorpening, M. P. Buric, and P. R. Ohodnicki, “Distributed optical fiber sensing: Review and perspective,” Appl. Phys. Rev., vol. 6, no. 4, Sep. 2019, Art. no. 041302.
[5] J. Wang, L. Wei, R. Li, Q. Liu, L. Yu, T. Li, and Y. Tan, “An FBG-based 2-D vibration sensor with adjustable sensitivity,” IEEE Sensors J., vol. 17, no. 15, pp. 4716–4724, Aug. 2017.
[6] Y. Xu P. Lu, Z. Qin, J. Harris, F. Baset, P. Lu, V. R. Bhardwaj, and X. Bao “Vibration sensing using a tapered bend-insensitive fiber based Mach-Zehnder interferometer,” Opt. Express, vol. 21, no. 3, pp. 3031–3042, 2013.
[7] Y. Zhao, F. Xiu, M.-Q. Chen, and R.-Q. Lv, “Optical fiber low-frequency vibration sensor based on butterfly-shape mach-zehnder interferometer,” Sens. Actuators A, Phys., vol. 273, pp. 107–112, Apr. 2018.
[8] S. Wu, L. Wang, X. Chen, and B. Zhou, “Flexible optical fiber Fabry–Perot interferometer based acoustic and mechanical vibration sensor,” J. Lightw. Technol., vol. 36, no. 11, pp. 2216–2221, Jun. 1, 2018.
[9] M. Han, T. Liu, L. Hu, and Q. Zhang, “Intensity-demodulated fiber-ring laser sensor system for acoustic emission detection,” Opt. Express, vol. 21, no. 24, pp. 29269, 2013.
[10] T. Liu, L. Hu, and M. Han, “Adaptive ultrasonic sensor using a fiber ring laser with tandem fiber Bragg gratings,” Opt. Lett., vol. 39, no. 15, p. 4462, 2014.
[11] Q. Wu, Y. Semenova, P. Wang, and G. Farrell, “High sensitivity SMS fiber structure based refractometer-analysis and experiment,” Opt. Express, vol. 19, no. 9, pp. 7937, 2011.
[12] Q. Wang, G. Farrell, and W. Yan, “Investigation on Single-Mode–Multimode–single-mode fiber structure,” J. Lightw. Technol., vol. 26, no. 5, pp. 512–519, Mar. 1, 2008.
[13] K. Tian, X. Wang, G. Farrell, and P. Wang, “Single-mode-multimode-single-mode fibre structure for sensing applications: A review,” in Proc. Adv. Photon., 2018, Paper SeM4E.1, pp. 1–8.
[14] J. Hansen, M. Sato, V. Masson-Delmotte, and F. Ackerman, “Assessing ‘dangerous climate change’: Required reduction of carbon emissions to protect young people, future generations and nature,” PLoS ONE, vol. 8, no. 12, 2013, Art. no. e81648.
[15] M. Dong, C. Zheng, S. Miao, Y. Zhang, Q. Du, and Y. Wang, “Development and measurement of a mid-infrared multi-gas sensor system for CO, CO$_2$, and CH$_4$ detection,” Sensors, vol. 17, no. 10, p. 2221, 2017.
[16] A. Boubena, A. Haifaiba, A. Khouzou, K. Mohameddi, and M. Becherif, “Carbone dioxide capture and utilization in gas turbine plants via the integration of power to gas,” Petroleum, vol. 3, no. 1, pp. 127–137, Mar. 2017.
[17] M. T. Yildirim and B. Kurt, “Aircraft gas turbine engine health monitoring system by real flight data,” Int. J. Aerosp. Eng., vol. 2018, Mar. 2018, Art. no. 9570873.