Novel Intracavity Sensing Network Based on Mode-Locked Fiber Laser

Yan Zhang, W. Jin, H. B. Yu, M. Zhang, Y. B. Liao, H. L. Ho, M. S. Demokan, G. Stewart, B. Culshaw, and Y. H. Li

***Abstract*—The authors report a novel technique for interrogating a network of intracavity absorption sensors. The technique is based on a mode-locking principle where different sensors are addressed by their associated mode-locking frequencies. Experiments with a two-sensor network demonstrated negligible crosstalk between sensors and a sensitivity of 128 times better than that of a single-pass direct absorption sensor.**

***Index Terms*—Gas sensor, intracavity spectroscopy, mode lock, multipoint measurement.**

I. Introduction

FIBER-OPTIC sensors based on direct absorption spectroscopy have been exploited for trace gas detection and other applications [1]. The advantages of fiber sensors over conventional techniques include immunity to electromagnetic interference, remote sensing, and networking capability. Recently, cost-effective multipoint fiber-optic gas sensor systems have been demonstrated [2]. High-sensitivity measurements were achieved by reducing various noises through the use of wavelength modulation spectroscopy and digital filtering techniques [3]. An alternative technique to achieve high-sensitivity absorption measurement is to use intracavity spectroscopy where an absorber is directly placed within the cavity of a laser [4]. The large number of passes through the absorber within the cavity effectively transforms a short absorption cell into a highly efficient multipass system and thus improves the detection sensitivity. The implementation of intracavity spectroscopy in a fiber-optic format would allow a detection system with the high sensitivity of intracavity detection and the advantages of fiber-optic sensors [5], [6]. The fiber-optic systems use key components such as fiber amplifiers that are developed for communications applications and thus allow for cost-effective sensors to be developed. The broad gain spectrum of the fiber amplifier [e.g., erbium-doped fiber amplifier (EDFA)] covers the overtone absorption lines of a number of important gases, permitting multigas detection with the same intracavity sensor, and would allow for further cost reduction in terms of cost per type of gas. However, the cost of the intracavity system is still high due to the use of the relative expensive components such as EDFA [7]. In this letter, we report a novel technique for multiplexing intracavity spectroscopy sensors. All the sensors within the network share common expensive components and a signal processing unit and thus reduce the cost per sensing point. The initial results of this work have also been reported in [8].

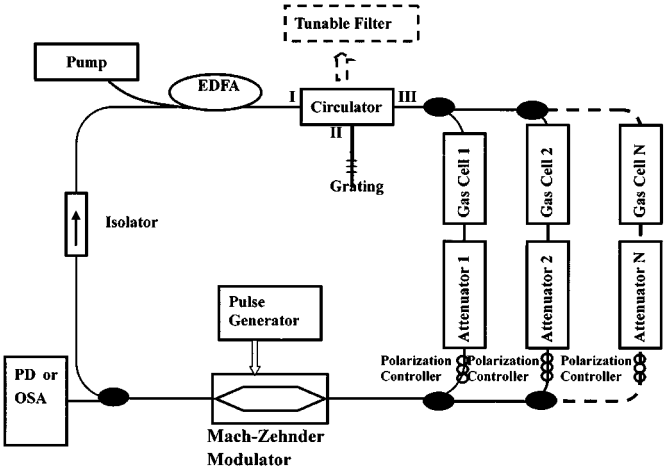

Fig. 1. Schematic diagram of the multipoint sensing network using a mode-locked fiber ring laser. EDFA: Erbium-doped fiber amplifier. PD: Photo detector, OSA: Optical spectrum analyzer.

II. Principle of Operation

The basic configuration of the multipoint intracavity gas sensor system is shown in Fig. 1. N gas sensors made from microoptic gas cells [2], [3] are connected in a ladder topology and further connected to a common optical path consisting of an EDFA, a tunable optical filter and an intensity modulator. The system may be regarded as N fiber ring laser cavities sharing a common gain medium. The intensity modulator within the cavity acts as a switch and can be controlled by a signal with variable repetition rate. The switch is closed only for very short duration so that continuous-wave (CW) oscillation is inhibited. However, if the repetition rate is matched to the characteristic frequency of a cavity, say cavity i that contains sensor i, i.e., [9]

$$f = N_i f_i = N_i \frac{c}{L_i} \tag{1}$$

where c is the speed of the light in vacuum, L_i is the optical length of the ith cavity that includes the optical length of the fiber and the gas cell, and N_i is an arbitrary integer, a pulse would circulate in the cavity, traversing the modulator with low loss on each pass because at that instant the switch is closed. The result is the generation of mode-locked pulses oscillating at

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a multiple of the characteristic frequency of loop $i(f_i)$. It should be mentioned that variation in gas concentration may affect the refractive index of the gas and, therefore, the length and the characteristic frequency of the cavity; however, this effect is on the order of 10^{-6} or less [10] (for 1-cm gas cell) and hence can be neglected.

The dependence of mode-locking frequency on cavity length can be used to address different gas sensors. As gas cells are placed within cavities of different lengths, a cavity can only oscillate and provide lasing output when the repetition rate of the modulation signal is matched to that of the cavity. We can therefore interrogate the different cavities (sensors) by varying the repetition rate and obtain mode-locked pulses from each cavity in turn.

We now look at the relationship between the output power of a particular selected cavity and the associated cavity loss. We start from a CW EDF laser, and the output intensity of such a laser may be expressed as [11]

$$I_0^{cw} = \frac{A}{\delta} - B = \frac{A - B\delta}{\delta} \tag{2}$$

where A and B are functions of pump power and other system parameters. δ is the loss in the cavity. The threshold condition is given by $A - B\delta = 0$. Assume that there are M oscillating modes with equal amplitudes that have been locked in the system, the average laser intensity (I_0) over a time period significantly longer than the period of the mode-locked pulses may be expressed as [9]

$$I_0 \propto \left(\frac{1}{T_i} \int_0^{T_i} \frac{\sin^2(M\pi f_i t)}{\sin^2(\pi f_i t)} \right) I_0^{cw} \propto I_0^{cw} \tag{3}$$

where $T_i = 1/f_i$. Equations (2) and (3) tell us that the average laser output I_0 is inversely proportional to the intracavity loss δ and can therefore be used to measure the variation in the intracavity loss.

For absorption measurement, the output power variation in decibels (i.e, $10\log I/I_0$) is usually measured, where $I = I_0 + \Delta I$, ΔI represents an incremental variation in I_0 due to a small change in the intracavity loss $(\Delta\delta)$. They are related as $10\log(I/I_0) \propto (\Delta I/I_0) \propto (A/\delta(A - B\delta))\Delta\delta$. The system sensitivity to a small cavity loss variation is inversely proportional to $A - B\delta$ and will be significantly increased if the laser is working close to the threshold where $A - B\delta$ approaches zero.

III. Experiments and Results

Experiments were carried out with the setup $(N = 2)$ shown in Fig. 1. The EDF was pumped by a 980-nm laser diode. A combination of a fiber Bragg grating (FBG) and a circulator is used as a tunable filter to select the working wavelength of the laser. The use of a circulator and an isolator as shown in Fig. 1 ensures unidirectional laser operation in the cavities. The lengths of two cavities are respectively 373 and 267 m, corresponding to the characteristic mode-locking frequency of $f_1 = 536$ kHz and $f_2 = 749$ kHz. A Mach–Zehnder-type integrated optical intensity modulator driven by a Telulex model SG-100/A pulse generator with variable repetition rate was used to achieve mode locking. As modulation property of the modulator is sensitive to input polarization state, polarization controllers were used in cavities to ensure optimal modulation. During experiments, the polarization states were found fluctuating with a typical time constant of about 30 min, due to environmental disturbances such as temperature. This problem may be overcome by using real-time polarization controllers or depolarizers. A 1:99 fiber coupler is used to extract signal from the cavity to a photo detector (PD) or an optical spectrum analyzer (OSA).

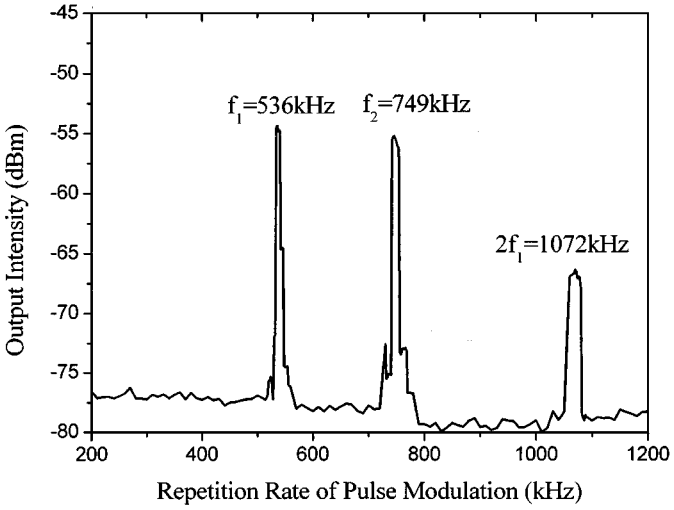

Fig. 2. Laser output intensity at different modulation frequencies.

Mode-locked pulses were observed at the PD output when the repetition rate is tuned to the mode-locking frequency of one of the cavities, i.e., 536 or 749 kHz. The spectral width of the mode-locked laser pulses was measured using the OSA to be 0.08 nm, limited by the OSA resolution (0.08 nm). The real spectral width could be smaller than this value.

Fig. 2 shows average output power from the PD when the repetition rate of the pulse modulation is varied from 200 to 1200 kHz. The three peaks in the figure correspond, respectively, to the fundamental frequencies (f_1 and f_2) of the two cavities and the second harmonics $(2f_1)$ of the first cavity. The electronic spectral bandwidths at -10 dB for f_1 and f_2 components are about 10 kHz, which would set the limit to the minimum frequency interval between two cavities. The second harmonic can also be seen and could be used instead of the fundamental frequency if this was more convenient. Assume that we use the fundamental frequencies to detect signals and the mode-locking frequencies satisfy $f_1 < f_2 < \cdots < f_N$, to avoid significant crosstalk between cavities, the condition $2f_1 > f_N$ should be satisfied. Assume equal frequency interval of $\Delta f = 10$ kHz between adjacent cavities, the maximum sensor number for our present system may be estimated as $536/10 \approx 53$.

By tuning the repetition rate to respectively 536 and 749 kHz, we measured the mode-locked output (in dBm) for both cavities when the intracavity loss was varied by using variable attenuators. Fig. 3 shows the results for a pump laser driving current of 150 mA. Within the operating region, as shown in Fig. 3, the output power variations are, respectively, 21 and 6 times of that of the intracavity loss variation, indicating 21 and 6 times enhancement of the detection sensitivity over the conventional single pass direction absorption measurement. The difference in the enhancement factors for the two cavities is because the two

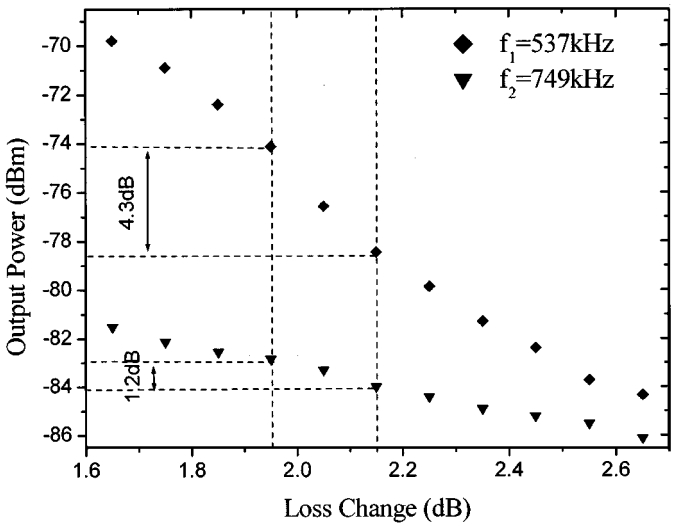

Fig. 3. Output power variation of the two cavities when the cavities losses are varied.

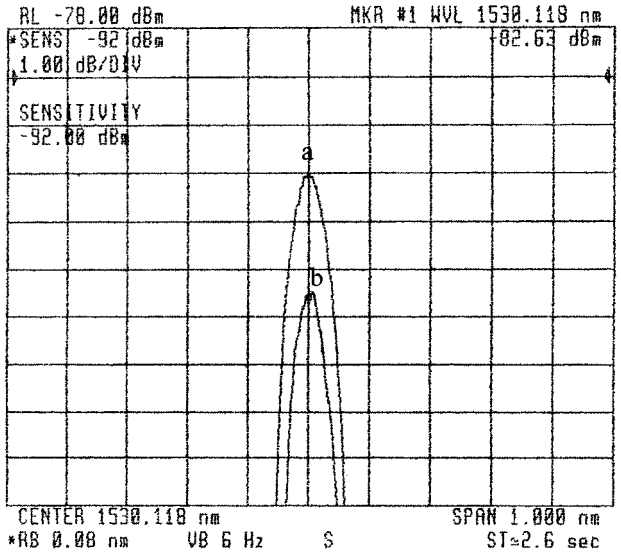

Fig. 4. Output light spectrums when the modulation repetition rate is $f_1 = 536$ kHz: (a) without and (b) with 1% acetylene gas.

cavities have different intrinsic loss and the first cavity is closer to its threshold (measured to be ~140 mA).

The crosstalk characteristics of the system was studied by examining the PD output when the repetition rate of the modulation signals were tuned to the characteristic frequency of one of the cavities (e.g., 536 kHz for cavity 1) while varying the loss in the other cavity. The signal variation was found below noise level, indicating negligible crosstalk between the two sensors.

The system was then used for detecting acetylene gas. By applying strain to the grating, the laser wavelength was adjusted to 1530.12 nm, corresponding to one of absorbing peaks of acetylene gas. To obtain higher sensitivity, we decrease the pump current to 145 mA which is close to threshold value of cavity 1 (140 mA). Fig. 4 shows the spectra of fiber laser output measured using the OSA when the modulation repetition rate was tuned to $f_1 = 536$ kHz. The peak value dropped 2.56 dB when the gas cell (1 cm long) in cavity 1 was filled with 1% of acetylene gas. The single pass direct absorption loss of the cell was measured by filling the cell with the same gas concentration and found to be 0.02 dB. This represents a sensitivity enhancement factor of 128 times in terms of output peak intensity variation over that of the single pass loss. The peak intensity of the laser output was found fluctuating slightly with a standard deviation of 0.20 dB, corresponding to a measurement error in terms of minimum detectable (acetylene) gas concentration of 781 ppm. For cavity 2, the sensitivity enhancement factor is 42 times and the measurement error is 2400 ppm. The laser output fluctuations may be due to the instability of the pump laser, polarization effect, and various environmental effects. Further work is needed to minimize these effects and optimize the system performance.

IV. Summary

An active mode-locked fiber laser configuration was proposed for multipoint intracavity absorption measurement. Theoretical analysis shows that the technique can be used to multiplex a few tens of sensors. Preliminary experiments with a two-sensor system showed that the output peak intensity variations are 128 and 42 times (for the two sensors, respectively) the single-pass direct absorption measurement. The minimum detectable gas (acetylene) concentrations for the two sensors are, respectively, 781 and 2400 ppm with 1-cm-long gas cells.

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