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"Fiber-Optic Cavities for Physical and Chemical Sensing"

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Abstract: Fiber-optic resonators can be used as ideal mechanical probes and chemical sensors owing to their unique sensitivity to static and dynamic strain applied to the fiber as well as to optical absorption or refractive index changes in the surrounding medium when the evanescent or the internal light field is exposed. The intrinsic properties of high-finesse fiber cavities, either based on Bragg-grating structures or closed fiber rings, are discussed for quasi-static and dynamic strain sensing. Laser illumination and high precision laser frequency-locking techniques are considered for low-noise, fast and wide dynamic range active interrogation. Also, possible detection schemes for liquid sensing and spectroscopy using fiber resonators are illustrated using single-frequency tunable lasers or supercontinuum comb generators as light sources.

Keywords: Optical fiber, Optical cavity, Fiber Bragg grating, Laser, Frequency locking, Strain sensing, Cavity ring-down spectroscopy.

1. INTRODUCTION

Among optical sensors, fiber Bragg-grating (FBG) based resonant structures, such as fiber Fabry-Pèrot cavities and π-phase shifted FBGs, characterized by highly dispersive power near resonance, can be exploited to measure sub-pm length perturbations over a wide range of Fourier frequencies. The best performances have been demonstrated using sophisticated systems based on narrow-band laser sources and laser frequency stabilization methods, bringing resolution limit to the 10^{-10} level and below for quasi-static and dynamic strain sensing [1]. As a consequence, acceleration and acoustic sensing are feasible using the fiber-resonator sensor as an optical transducer.

On the other hand, optical resonators based on fiber periodic or ring-like structures have been successfully employed for refractive index, gas and liquid sensing [2]. Cavity-enhanced and ring-down techniques allow detecting light-matter interaction in either direct or evanescent-wave spectroscopy configurations [3], using lasers or broad-band light. This class of sensors has the advantage of being compact, cheap, easy to use and, in addition, minimally invasive for analysis of small-volume samples.

Here, we will give a review of mechanical sensors that are based on fiber-cavities and interrogated with spectroscopic methods, in contrast to the most conventional interferometric and spectrally-dispersive techniques. Then, we also show how it is possible to extend such an approach to chemical sensing and spectroscopy in the liquid phase using a fiber probe.

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2. FIBER OPTIC RESONATORS IN STRAIN AND ACCELERATION SENSING SCHEMES

A fiber Fabry-Pérot resonator can easily be fabricated using gratings directly written in single-mode (SM) optical fibers. A *Bragg* grating written in optical fiber (FBG) consists of a periodic modulation of the fiber core refractive index, created using UV interferometric inscription techniques, that generates an intrinsic narrow-band reflector whose reflectivity spectrum is centered around the Bragg wavelength $\lambda_B = 2n_{eff}P$, where P is the grating pitch and n_{eff} the effective refractive index of the propagating mode. This center wavelength can be tuned by altering the fiber length or refractive index (e.g. by changing the temperature), and the peak reflectivity can be > 99.9 %. A high-finesse resonator is readily built by writing two high-reflectivity single-mode FBGs separated by a fixed distance L along the same fiber. The so-formed optical cavity behaves in the same way as a standard mirror cavity except that in a SM fiber only the axial modes are allowed to oscillate. The transmitted (as well as the reflected) field can be described with the same mathematical expressions as any Fabry-Pérot resonator [4], thus showing the typical periodic peak resonance spectrum. An example of the cavity transmitted spectrum is shown in Fig. (**1**) as obtained by a wide wavelength sweep of a diode laser in the telecommunication spectral region [5].

Finesse values exceeding 1000 are feasible. Upon stretching or compression of the fiber, optical pathlength variations ΔL of the intra-cavity fiber are turned into frequency shifts of the resonance frequency position $\Delta\nu$. In fact, it is easy to see that [6]

$$\Delta\nu \cong -0.78 \cdot \nu \cdot \frac{\Delta L}{L} \quad (1)$$

where the 'correction factor' 0.78 is necessary to account for the elasto-optic change of refractive index due to mechanical strain of the fiber $\varepsilon = \frac{\Delta L}{L}$. The cavity thereby transforms a strain into a very large shift or modulation (depending whether it is static or dynamic) of its transmission and reflection peak position. In principle, also the cavity photon lifetime, or analogously the free-spectral-range, is affected by intra-cavity length although this is a much weaker effect. The strain-to-frequency response of the resonator in Eq. (1) appears as a sort of *leverage* process via the optical frequency ν and it is amplified as a consequence of multiple-passes of light through the internal cavity fiber which is affected by length changes. The quality of the resonator plays the relevant role in this regard: the larger is the finesse, the longer is the effective pathlength travelled by the light through the fiber. On the other hand, since mechanical strain is detected from the resonance shift, the cavity enhancement leads to higher spectral resolution because the cavity mode linewidth is proportional to the ratio between the mode spacing (free spectral range) and the finesse. Measuring the resonance frequency position is thus very convenient to fully exploit the FBG cavity as a mechanical sensor. Although the working principle of fiber resonators is quite straightforward, in order to achieve very low noise interrogation, sophisticated read-out methods need to be developed. Conventional interrogation approaches are based on broad-band, incoherent light sources that illuminate the sensor and provide a signal that is modulated with the strain on the fiber. Readout of amplitude changes from that signal provides information on the strain experienced by the fiber. A reversed approach is possible, which is based on monochromatic light as inspired to high-sensitivity and resolution spectroscopy schemes. Using narrow-band lasers instead of incoherent light, not only increases the power density upon detection above the photodetector's *noise-equivalent power* (NEP), but also increases the optical resolution, thanks to the intrinsically narrower emission spectrum. In addition, when using tunable lasers, active tracking of the sensor is possible thereby improving bandwidth and dynamic range. The resulting frequency response can be exceedingly high, as we will show in the following. A first possible set-up is represented in [7]. A diode laser (DL) is actively locked to the resonator by an opto-electronic feedback loop that is based on the Pound-Drever-Hall (PDH) scheme [8, 9]. Basically, the laser beam that is reflected by an optical cavity is the coherent sum of two contributions: a promptly reflected beam that bounces back from the input mirror and a leakage beam that comes from the cavity due to imperfect reflectivity of the mirror. When the laser is perfectly resonant, the promptly reflected and the cavity back-transmitted fields are equal in amplitude but out of phase (180 °) and thus they interfere destructively. In PDH method, the laser is phase modulated at frequency *f*. Two new fields (sidebands) are thus symmetrically generated on the laser beam at a frequency distance *f* from the carrier. These sidebands are used as a phase reference with which one can measure the phase of the reflected beam. In general, they are totally reflected by the input mirror and may interfere with the cavity back-reflected field. The beats between the sidebands and the reflected carrier provide the phase difference between the reflected beam and the cavity resonance, i.e. an error signal that quantifies the deviation of the laser from the resonance. On perfect resonance, the side-band-carrier beat signals are identical in amplitude and phase and yield an overall zero signal. Any shift from this condition leads to a signal whose amplitude depends on the relative position between the laser and the cavity mode while its sign indicates the direction in which the laser is moving from the resonance. The PDH error signal can be generated first modulating the diode-laser phase via a high-frequency bias-tee current input and then collecting the reflected power through a fiber circulator and heterodyning it with the modulation signal in a double-balanced mixer. The latter is sent to a proportional-integrative amplifier (servo). With the loop gain at its highest value (before self-oscillation), the laser remains perfectly stable on the cavity mode. In this way, the laser is kept always on the resonance peak of the sensor while the feedback signal contains the desired strain information [5]. With this in mind, any mechanical or thermal stress applied to the cavity immediately translates to amplitude changes at the servo output, thus providing a fast and sensitive strain monitor at frequencies from DC to the unity-gain frequency of the locking loop.

A different way to interrogate a FBG Fabry-Pérot sensor consists in locking a diode laser to a fiber resonator by an extension of the polarization-spectroscopy scheme originally developed by Hansch *et al.* [10]. It was theoretically investigated and experimentally demonstrated that the anisotropy induced into the FBG during the inscription process [11], combined with the natural birefringence of the pristine fiber, gives rise to the same ellipticity effect as that caused by a polarizer internal to the cavity. The experimental set-up is illustrated in Fig. (**2**). A FBG Fabry-Pérot (FBGFP) sensor operating as a static and dynamic strain probe using the intracavity fiber as a sensitive element have been successfully demonstrated in this fashion by our group [12]. This can be accomplished without using any phase/frequency modulation or sophisticated electronic equipment. Given the limitation of the free-running laser-frequency jitter, the performance of such system proved comparable with a PDH scheme using an unstabilized laser diode, while the tracking action was found to be as stable and reliable in the long-term operation.

In Fig. (**3**), the response of the locking servo signal to a 0.7-nε rms strain on the intracavity fiber is shown. The noise level on the background corresponds to a strain resolution of about 1 pε (1 pε = 10^{-12} fractional length change). The depth of the laser modulation due to the applied strain can be accurately calibrated using RF sidebands as a precise ruler and the strain can be related to the PZT bias voltage at different modulation frequencies through Eq. (1). In addition to the applied perturbations, satellite oscillations are also visible from 50 to 350 Hz. These may be consequence of cross-talk from the ac power supply as well as environmental noise that couples to the fiber. The limit to the minimum detectable strain is dictated by the laser frequency noise. This aspect will be discussed in detail in the following sections.

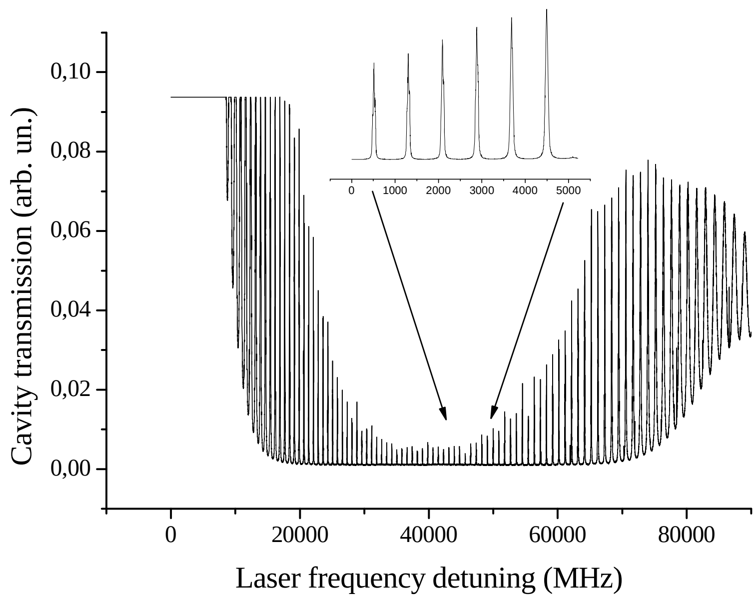

Fig. (1). Power transmission of a FBG Fabry-Pérot cavity in silica fiber (From ref. 5. @ IOP Publishing. Reproduced by permission of IOP Publishing. All right reserved).

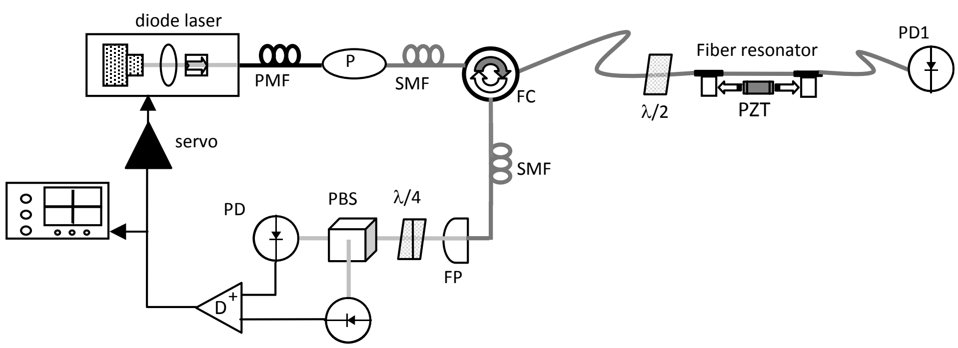

Fig. (2). Strain sensing with polarization spectroscopy-locking of a laser diode to a FBG resonator (reprinted with permission from ref. 12).

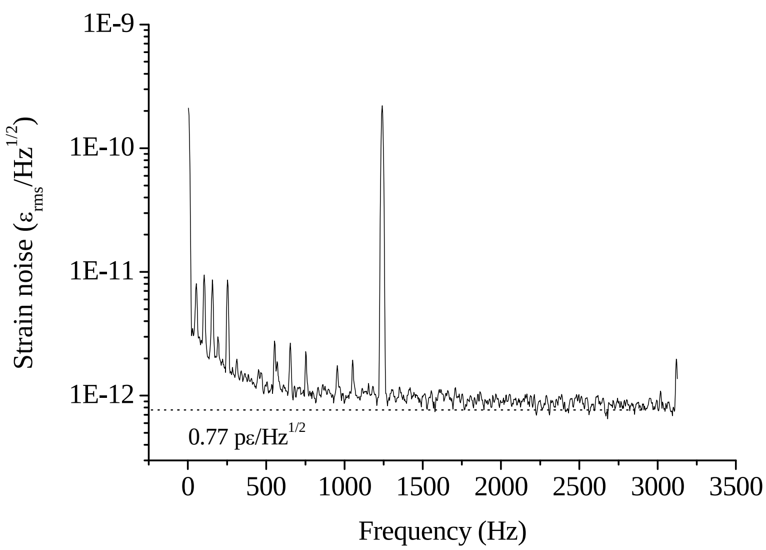

Fig. (3). Correction signal (servo) for dynamic elongation of the FBG resonator fiber (length 10 cm, finesse 300) around 1.2 kHz. Servo voltage may be expressed in terms of the fiber strain by calibrating an external piezo actuator (reprinted with permission from ref. 12).

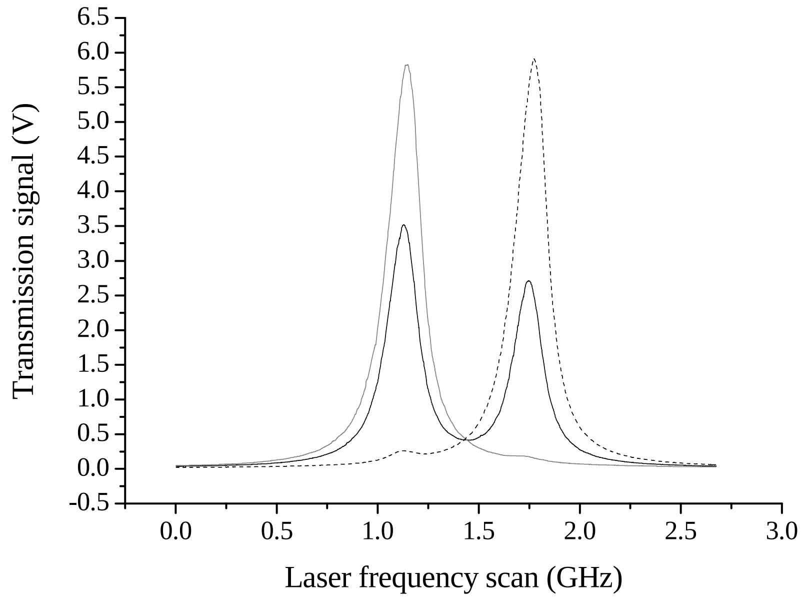

Fig. (4). Central resonance within the Bragg curve of a π-phase-shifted grating with a reflectivity of ~ 99.6 %. The peaks correspond to orthogonal polarization states in the fiber, due to weak silica polarization-mode dispersion. Dotted curve: fast polarization; dashed curve: slow polarization; solid line: 45° linear polarization (From ref. 16. @ IOP Publishing. Reproduced by permission of IOP Publishing. All right reserved).

An analogous system for strain and pressure sensing can be developed using a ring optical cavity built around a fiber biconical taper [13]. The interrogation system is based on cavity ring-down measurements and loss variations due to mechanical perturbation of the taper. The method is attractive because it doesn't use any complicated set-up or sophisticated sensor head. The detection limit seems appropriate for many applications (~ 80 nε/√Hz) although no characterization has been performed on its response to dynamic perturbations (e.g. vibration, acceleration). However, the performance is not comparable to that achievable in a FBG cavity by tracking of the cavity-mode shift, which benefits from the huge leverage effect shown by Eq. (1). Using a biconical fiber taper, the ability to extract the strain information depends strongly on the exponential time-decay fitting procedure employed and appears not suitable for real-time monitoring/tracking of fast strain signals unless very sophisticated acquisition electronics is adopted. Moreover, the sensing element is extremely fragile and shows a non-linear response due to excitation of higher-order fiber modes when a deformation is applied.

Similarly to in-fiber Bragg resonators, π-phase shifted FBGs (PSFBGs) have been proposed for strain sensing too. PSFBGs are very attractive for strain sensing as they have a short gauge length (~ few mm), similar to standard FBGs, but exhibit the unique spectral features of optical resonators, i.e. a very high dispersive power around the resonance [14]. On the other hand, PSFBGs are easier to fabricate than standard FBG resonators since they comprise just one grating, and no wavelength matching is required. Furthermore, PSFBGs can be written with a reflectivity > 99 % and are thus well suited for developing small-size (large bandwidth) opto-mechanical sensors of high quality. The transmission feature of a PSFBG looks like the plot shown in Fig. (**4**).

Very recently, high-sensitivity interrogation schemes based on a frequency-stabilized laser were proposed for PSFBGs [15]. A strain resolution in the order of 10 pε/√Hz was demonstrated in the audio and ultra-sonic range (≥ 1 kHz) with an extended-cavity diode laser locked by a PDH system. The achievable resolution is limited at lower frequencies, most likely due to laser excess (flicker) noise as well as mechanical instabilities of the laser cavity. Subsequently, using PSFBGs, a miniature fiber-based 3-axis accelerometer suitable for seismic and vibration sensing was built [16]. Indeed, velocities and accelerations can be efficiently measured using a fiber-optic probe integrated with an inertial mass or beam, provided the mechanical response of the solid element is known. Three separate PSFBGs were attached to three cantilever beams aligned along orthogonal planes, as shown in Fig. (**5**). The sensors were interrogated by three telecom distributed-feedback (DFB) DLs actively locked to their central resonances by the PDH technique. Near-infrared DFB DLs have the advantage of being cheap, easily available from the telecom market and rather insensitive to environmental acoustic noise. An acceleration noise-floor of 10 μg/√Hz between 10 Hz and 1 kHz was readily achieved. This sensitivity level compares well with the typical performance of seismic accelerometers, with the advantage of a much higher frequency response. At very low frequencies, the resolution is reduced due to the characteristic 1/f noise roll-up when approaching DC.

3. ULTRA-HIGH SENSITIVITY STRAIN MEASUREMENTS

In principle, a rigorous assessment of fiber-resonator sensitivity limits in mechanical sensing should start from the shot-noise-limited frequency noise spectral density of the PDH locking method [17]

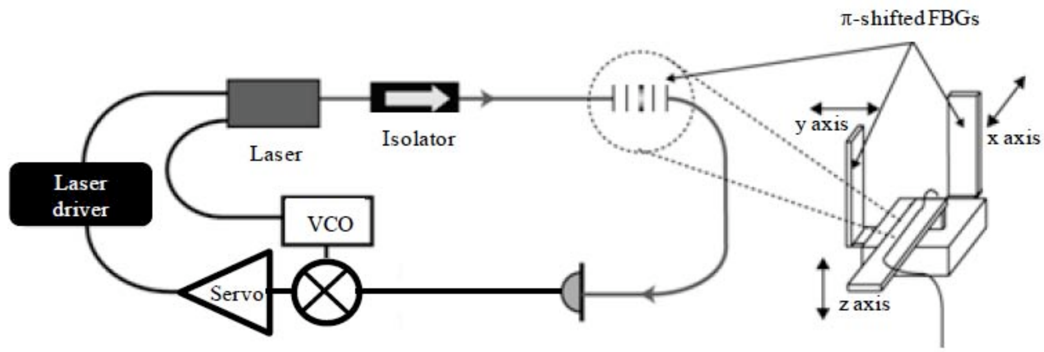

Fig. (5). A simple sketch of the interrogation set-up used for 3-axis acceleration sensing with PSFBGs (From ref. 16. @ IOP Publishing. Reproduced by permission of IOP Publishing. All right reserved).

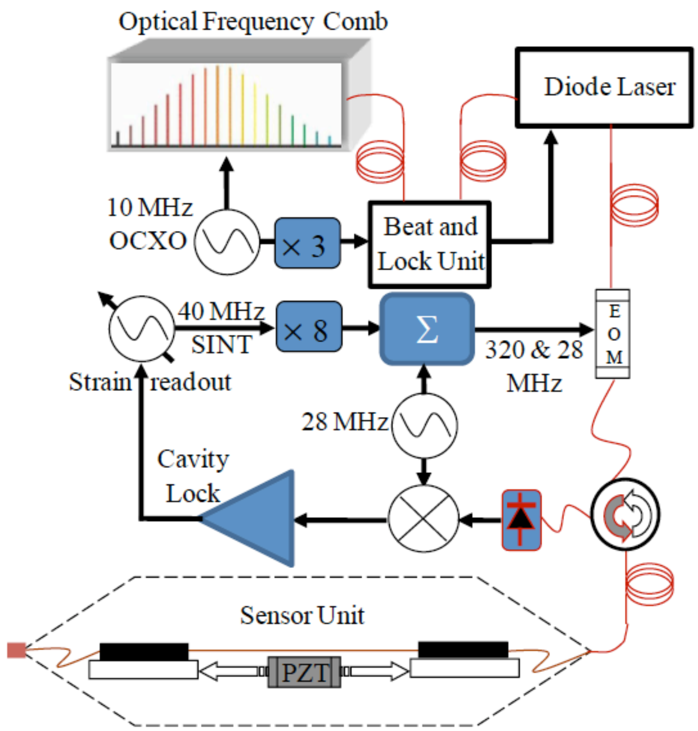

Fig. (6). Optical comb-based interrogation system for high-resolution strain measurement with FBG resonators at low and high frequencies (From ref. 30. Reprinted with permission from AAAS).

$$S_{PDH}(Hz/\sqrt{Hz}) = \frac{\Delta\nu_c}{J_0(\beta)}\sqrt{\frac{h\nu}{8\eta P_i}} \quad (2)$$

For example, a cavity mode linewidth $\Delta\nu_c$= 2 MHz, detector efficiency η ~ 0.9, incident power P_i = 0.1 mW and modulation depth β = 0.3, which are quite common values, a strain noise level $\varepsilon_{PDH} = {S_{PDH}}/{0.78\nu} \cong$ 0.14 fε/√Hz is obtained from Eq. (2). However, a more realistic approach must include the unavoidable phase and frequency fluctuations associated with the free-running laser. Assuming that the laser is dominated by spontaneous-emission frequency noise, its emission spectrum will be Lorentzian. For DFB DLs, for instance, a linewidth in the order of at least 10-50 MHz is expected, which can be converted from Eq. (1) to cavity length fluctuations, i.e. strain noise, yielding an ultimate strain resolution of about 10-50 pε/√Hz. This result agrees well with experimental findings, as shown in the previous section.

Pre-stabilized lasers may provide benefits in this regard. Chow *et al.* locked a low-power extended-cavity diode laser emitting at 1550 nm to a high-finesse free-space reference cavity to suppress its free-running frequency noise and then used it for interrogation of a FBGFP cavity [17]. Adopting the PDH frequency lock for active tracking of the sensor, subpicostrain signals could be detected, at frequencies from 100 Hz to beyond 100 kHz.

A brief mention is due on the famous fiber-laser sensors which were developed in the early 90s based on interferometric interrogation [18]. In these sensors, the sensitive element is the fiber laser itself where the optical phase modulation caused by the strain action leads to a change in the interferometer signal. Impressive resolution levels, down to ~ 10 fε/√Hz (@ 8 kHz), were demonstrated in this fashion. However, this performance was achieved only in the high frequency acoustic (and ultrasonic) range where most typical noise sources (e.g. laser jitter, electronic noise, environmental noise etc.) are contributing much less to sensor interrogation.

A sensor capable of tracking very slow deformations with high resolution and accuracy would find important applications in several fields, including telescope control, inertial sensing, seismic monitoring and nanotechnology process analysis, among others. Also, low-frequency fibre interrogation techniques may have an impact in chemical sensing, e.g. with opto-acoustic resonators and optical microcavities. Indeed, in all such applications, the involved physical quantities change very slowly. On the other hand, quasi-static sensing is always challenging, as it suffers from unwanted laser frequency fluctuations and drifts in the interrogation unit caused by thermal effects as well as electronic noise at infrasonic frequencies. The use of optical frequency references significantly improves the long-term stability, leading to a greatly enhanced sensing performance.

Notable attempts towards laser stabilization for fibre sensing have been made in the past few years, relying on atomic and molecular transitions as well as long interferometers [19, 20]. Nevertheless, using external devices for noise suppression in the infrasonic range makes the (thermal and mechanical) stability prerequisites extremely demanding even for well-controlled laboratory systems. Very recently, Chow et al. used an easily available near-IR ro-vibrational transition of HCN as a stable reference for strain measurements by a FBG cavity sensor [21]. A fiber laser emitting at a wavelength of 1550 nm is locked to the HCN absorption line. The experiment demonstrates a large reduction of very low frequency laser instabilities with subsequent gain in terms of strain resolution, thereby leading to a limit of the order of 10 pε/√Hz in the 1-Hz frequency range. However, though the optical scheme looks very effective, it is also clear that any change in the gas cell thermodynamic conditions leads to drifts and instabilities that add to the strain noisefloor.

As is well known, the ultimate resolution performance of fiber-laser and interferometric fiber sensors is limited by thermally-induced phase noise (TPN). The physical problem is similar to Johnson's noise in electrical circuits, and can be treated in a way analogous to Nyquist's theorem starting from thermal equilibrium energy fluctuations [22]. Experiments were reported for long fiber-optic interferometers and Sagnac gyroscopes [23, 24]. The same kind of fluctuations appears in the low and high-frequency phase noise spectrum of fiber lasers [25]. This aspect has been experimentally investigated over the last few decades, and different models have been proposed [26, 27]. Nonetheless, none of them fully agrees with experimental findings, particularly in the low-frequency range. A pre-stabilized laser interrogation system provides a way to disclose the contribution of TPN over other effects that usually dominate the noise budget, as already discussed above.

Nowadays, optical frequency comb synthesizers (OFCSs) provide an exceptionally stable, absolute frequency grid from the XUV to the mid-infrared [28, 29]. Combs originate from short, mode-locked laser pulses that are equally time-spaced by a radio-frequency (RF) clock. In 2010, our group [30] reported an unprecedented resolution level in strain sensing using a passive FBGFP interrogated by a diode laser that is stabilised against an OFCS. A schematic of the set-up is shown in Fig. (**6**). The comb is phase-locked to a 10-MHz oven-controlled quartz oscillator (OCXO) that is ultimately linked to a Cs-disciplined Rb-clock to suppress very long-term frequency fluctuations. The free-running quartz exhibits a single-sided phase noise $L(f) \approx -122$ dBc/Hz at 1 Hz. The comb beam spans about 40 nm around 1560 nm and is all-fiber coupled with a 10 mW power.

The diode laser is first phase locked to the nearest comb tooth. Thus, the laser frequency f can be related to f_r and f_O through the expression

$$f = \pm f_{beat} \pm f_O + m \cdot f_r \tag{3}$$

where f_{beat} is the laser-comb beat-note frequency (given by an external synthesizer). Treating the OFCS as a 'rigid' multiplication gear of the OCXO with a scale factor N ($N \sim 192$ THz/10 MHz = 1.9×10^7), the laser noise can be calculated from $S_v(f) = N \cdot f\sqrt{2L(f)}$ ≈ 20 Hz/√Hz at 1 Hz. Any laser frequency fluctuation δv is thus converted into strain ε using Eq. (1). Two 'secondary carriers' are created by deep phase modulation using another tuneable synthesizer which is locked to a cavity mode by a PDH scheme. In this way, active interrogation of a 10-cm FBGFP cavity sensor is possible by the SC, with minimal frequency noise contribution, while the main laser carrier remains phase locked to the OFCS. In this way, the response of the sensor is brought very close to the fundamental limit imposed by the fiber thermodynamic noise, in a previously inaccessible frequency range. Strain readout is taken from the locking loop correction signal. A lower bound of 550 $f\varepsilon_{rms}$/√Hz around 2 Hz can be measured, with a minimum of 350 $f\varepsilon_{rms}$/√Hz at 5 Hz. The strain resolution achieved by comb-referenced interrogation of the FBGFP sensor is the best reported to date in the infrasonic frequency range. The sensor might no longer be limited by the residual locked laser stability but rather affected by TPN in the fiber resonator. However, a complete theoretical model for finite-cladding fibres is not available yet [31]. Moreover, a reliable estimate of the noise level is significantly affected by the uncertainty of the involved parameters while the correctness of the model has never been tested for very low frequencies. New experiments are still necessary to confirm or modify general theories of thermodynamic phase noise in optical fibers in the quasi-static regime.

4. OPTICAL FIBER CAVITIES FOR MUSICAL RECORDINGS

As was shown above, single FBGs and especially cavities made of two identical FBGs can be configured into very sensitive probes for strain and vibration. This would also make them broadband and low-noise pick-ups for musical instruments. All "acoustic" string instruments such as guitars, violins, and even cembalos or harps have a soundboard that amplifies the sound generated by the string movement. The exact shape of the soundboard determines the instrument

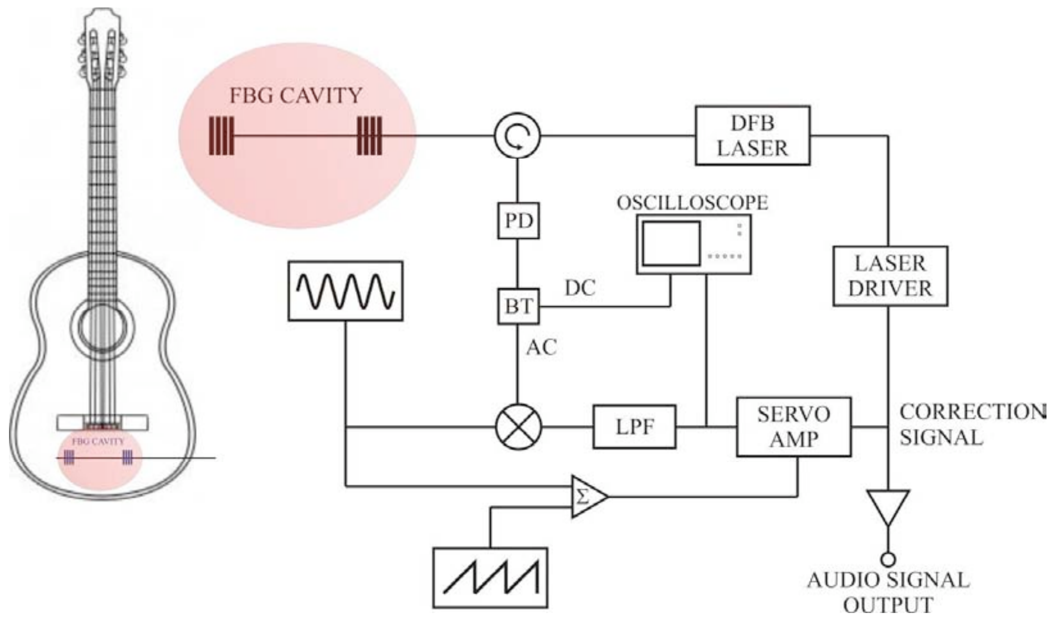

Fig. (7). Experimental scheme for music recording by a FBG cavity sensor [33]. DFB: distributed feedback; PD: Photodiode; BT: Bias Tee; LPF: 50 kHz low pass filter.

spectrum. Several musicians prefer to record the sound of their instrument using a high quality microphone, but this may be impractical in an environment with large background “noise” such as a performance stage. Many acoustic guitars and, to a much lesser extent, other string instruments are therefore equipped with piezoelectric transducers (PZT “pick-ups”) that are placed on the soundboard and convert its vibrations into an electrical signal. Although piezo pick-ups have a flat frequency response between about 100 Hz-20 kHz and are inexpensive, they also have comparably high inertia, and are difficult to amplify due to their high impedance. When many of these PZTs are mounted onto a single instrument, the vibrations of the soundboard may be affected and the instrument coloration may be altered.

Fiber optic transducers are ideal for such applications. Recently, the feasibility of acoustic transduction has been demonstrated by affixing a single FBG or a FBG Fabry-Pèrot resonator on a guitar body and comparing the recordings with those made by an attached PZT [32]. An in-fiber Fabry-Perot (FFP) cavity made from two identical FBGs can be used for vibration and strain measurements, since the resonances in the cavity spectrum depend on the cavity length and thereby, again, on the strain applied to the waveguide as shown by Eq. (1). By detection and audio sampling of the reflected light from a FFP cavity, compact and very lightweight transducers (“pick-ups”) for guitars, violins, harmonicas and other musical instruments with a soundboard can be realized. The quality of the recorded music was found to be comparable to that of commercial PZT transducers, covering the entire audible region of the audio spectrum (from about 20 Hz to 20 kHz). These earlier measurements were performed by recording the intensity of the light reflected at the mid-reflection point of the cavity mode of a low-finesse FBGFP [32].

Using an interrogation method that locks the frequency of the probe laser tightly to the audio-modulated cavity-reflection feature has some advantage over this approach: it makes the measurement almost immune to the laser amplitude noise, external distrurbances and thermal drifts; it reduces the influence of electronic noise and widens the dynamic range of the intrinsic sensor with a bandwidth that encompasses the entire audio spectrum. The acoustic strain information is contained again in the correction signal (feedback) that is generated to keep the laser locked.

The acoustic transducer designed in a more recent work consists of a fiber Fabry-Perot cavity containing two 23 dB FBGs positioned 2 centimeters apart (Fig. **7**) [34]. The cavity was attached to the guitar body (*Dagmar Guitar*) close to the bridge, where a conventional PZT pick-up (designed for classical guitars) was mounted for comparison. The piezo pick-up is a passive device and designed for use with classical guitars. A DFB DL operating around 1549 nm was locked to a cavity mode using the PDH technique. The correction signal contains frequency components corresponding to the vibrations of the guitar body, and hence, may be amplified and recorded, or it may be sent to a speaker to reproduce the music. The servo amplifier was designed to have a bandwidth of at least 30 kHz but a better performance is possible. A portion of the feedback correction signal was applied to a ×20 gain acoustic amplifier and then sampled by Adobe Audition 3.0 software for recording and analysis.

Several parameters have to be considered for assessing musical instrument transducer quality, i.e. response time and frequency response curve, the signal-to-noise level, and dynamic range of the amplitude measurement. An ideal transducer exhibits a very low noise floor, a sensor bandwidth spanning the range from a few Hertz to 44 kHz (the rate at which Compact Disks are sampled) and a flat frequency response curve from about 50 Hz to 20 kHz, i.e. over the entire audible region. Fig. (**8**) and experiments described in [34] give these parameters but they are not able to fully represent the quality of the sound recording, which can be appreciated from audio files such as those published as supplementary material in [34]. The results of audio recordings with the

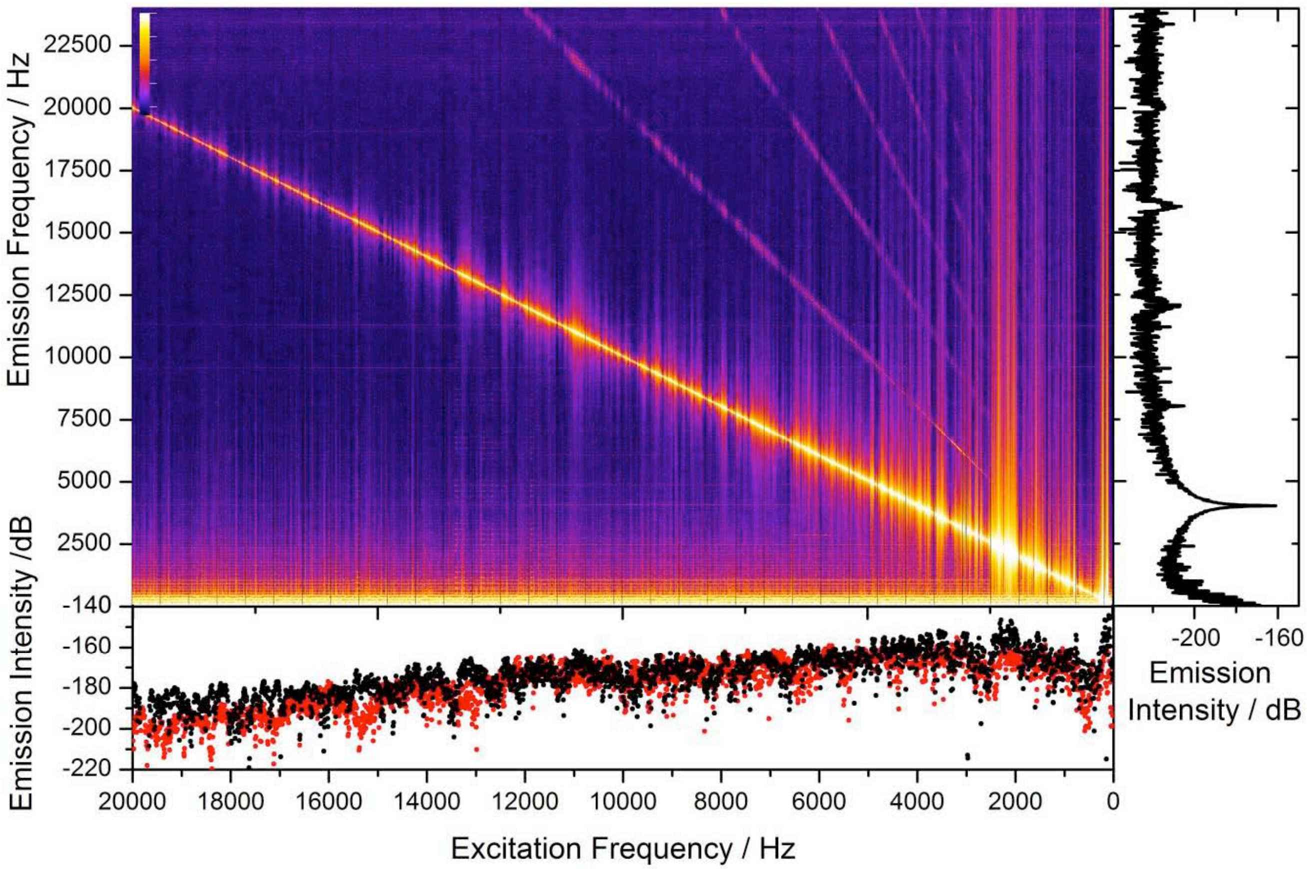

Fig. (8). Excitation-emission matrix spectrum showing the response of the guitar's soundboard to sound emitted from a speaker at different excitation frequencies. The FFP transducer reproduces the fundamental frequencies from about 30 Hz to 20000 Hz, as well as its overtones. Horizontal lines at multiples of 1 kHz are due to a weak clock signal from the computer's USB port. At frequencies above 13 kHz the FFP transducer response near the fundamental of the excitation frequency (black curve) shows a 5-10 dB stronger signal compared to the PZT pickup (red). The colour scale bar ranges from -220 to -180 dB. The curve in the right panel is the Fourier transform of the FFP cavity response at an excitation frequency 4 kHz (reprinted with permission from ref. 34).

fiber sensor appear definitely competitive with PZTs while the larger frequency response provides a slightly better sound for guitars. The amplitude of the soundboard vibration could not be measured directly while the acoustic guitar was played, but it can be estimated from the measured modulation of the cavity fringe wavelength. A modulation by about 5.7 pm (2.2 pm) was observed when the E_2 (E_4) string was played. Using a gauge factor of 0.78, this modulation amplitude corresponds to a strain of 4.7 με (1.8 με). Using a calibration obtained for a different guitar in an earlier publication, we can estimate the amplitude of vibration as approximately 90 μm (35 μm), which is consistent with earlier measurements (30-70 μm) for a slightly less "loud" instrument [32].

As mentioned above, the pickup is lightweight and may be multiplexed into a sensor array. It is therefore conceivable that multiple FFP cavity sensors may be embedded in the guitar body and – depending on their position – provide different timbres. Some high-end musical instruments already incorporate two or even more piezo pickups, giving a more balanced sound. Of course, one then requires a separate laser, laser driver, detector and locking electronics for each channel, whereas the power supplies, high-frequency generator and preamplifer may be shared. A prototype of such an instrument was recently built (Fig. **7**).

4. EVANESCENT-WAVE CHEMICAL SENSING WITH FIBER RING CAVITIES

Chemical sensors using fiber-optic technology underwent an extensive research and development activity with potential applications in industrial, environmental and biomedical monitoring. In this context, a miniature chemical sensor combining laser spectroscopy and state-of-the-art optical fiber devices may be suitable for in-situ, non-invasive gas or liquid analysis with high selectivity and sensitivity. This can be based on either direct or indirect (indicator-based) detection techniques. In the direct scheme, the optical properties of an analyte, such as refractive index (RI), absorption or emission, are measured directly. In the indirect scheme, the color or fluorescence of an immobilized label compound, or any other optically-detectable bioprocess, are monitored [35, 36]. In recent years, interrogation techniques have further advanced with the use of evanescent-wave spectroscopy and surface-plasmon resonance sensors [3, 37]. Sensors have also been incorporated into passive optical cavities consisting of fiber loops or linear fiber cavities defined e.g., by two identical FBGs [38, 39]. These cavities have been shown to be effective means of amplifying the sensors' response. Their applications to mechanical sensing have been reviewed in the previous sections of this paper. Optical microresonators, of different geometries, have also been proved as label-free and ultrasensitive chemical sensors over the past several years [40, 41]. In all cases above, a change in ambient refractive index may lead to a wavelength shift of the cavity modes, if part of the evanescent wave of the mode penetrates into the environment. On the other hand, if the molecules exhibit absorption lines or bands in the vicinity of the cavity resonance wavelength, the cavity lifetime, namely the ring-down time (RDT), will be reduced, along with the transmitted power through the resonator and the quality (Q-) factor.

Optical spectroscopy in the liquid phase also has an unrealized potential in the analysis of molecular species relevant to biomedical processes [42, 43]. In recent years, there have been only a few works on cavity-enhanced absorption spectroscopy of liquids using lasers or broadband light [44-46]. An effective and minimally-invasive method relies on using total internal reflection in optical fibers. In this case, the interaction with liquid chemicals in the surrounding environment may occur if the evanescent field is exposed along the external interface. Optical fibers are particularly suitable for in-situ, non-invasive sensing, even in environments with access difficulty, and lend themselves to the realization of multiplexed chemical probes. Furthermore, all-fiber resonators are cheap, compact, easy to build and they usually do not require special care in terms of alignment, cleaning and isolation.

On the other hand, when liquid spectroscopy is the main target, the required tunability can be demanding for a laser. If incoherent broadband sources are used in conjunction with high-finesse cavities, efficient coupling to the resonator modes is prevented, thereby dramatically reducing the available optical power. Furthermore, such a scheme is not immune to light-source intensity fluctuations, making it less sensitive than other CEAS and CRDS techniques.

The easiest way to build a resonator with an optical fiber is to create a closed fiber loop within which light remains confined. To inject light into the ring cavity one can splice commercial fiber couplers into the ring. Couplers can also be used to leak a small portion of the circulating light out of the cavity with each round trip. It is well known that a fiber loop ring cavity made from single-mode fiber behaves in a similar way to a conventional Fabry-Pérot resonator [4], exhibiting resonance modes spaced by the free-spectral-range, namely c/Λ ($\Lambda = nL$ where n is the fiber-core refractive index and L the total ring length). Light interaction with an absorbing sample, whether it be gaseous or liquid, can be probed either by the internal cavity field or the evanescent wave around the fiber, which can be exposed along a short portion of the fiber by partial removal of the cladding or by tapering processes. The evanescent-wave scheme is ideal for minimally-invasive analysis of small-volume liquid samples. A laser may be used for interrogation to extract the information on the intra-cavity absorption occasionally due to an external absorber.

Tarsa *et al.* [46] combined cavity ring-down spectroscopy (CRDS) with single-mode fiber loops to benefit from the versatility of fiber-optic sensing and the improved sensitivity of CRDS. They used a km-long fiber loop and interrogated it by means of a high-quality extended-cavity diode laser for evanescent-wave detection of a liquid absorption band. For this purpose, a tapered sensing region is fabricated along the fiber by a simple modification of the fiber shape that exposes the evanescent field. The resulting detection limit is in the order of $1.7\ 10^{-4}/\sqrt{\text{Hz}}$. Despite the unique tunability range of their laser, which is well beyond the typical performance of other diode lasers, the spectral coverage is only sufficient to recover a liquid band of only 25-nm width. Also, the bi-conical fiber taper represents a further limitation since it is hard to reproduce, quite fragile and rather impractical for real applications. Evanescent-wave access blocks that can be obtained by side-polishing of single-mode fibers [47] are more robust and reliable although special machines are necessary for fabrication. This is one of the reasons why other groups have chosen alternative approaches that rely on leaving a small gap within the fiber loop [48, 49] or devising special liquid interfaces to enable light-matter interaction [50].

A recent breakthrough was represented by coherent coupling of optical frequency combs (OFCs) to high finesse optical cavities used as sample compartments [51-53]. OFCs have the unique property of being highly coherent but emitting over a very wide spectral range, from the visible to the near-IR [54]. In such case, spectral analysis of cavity transmitted light can be performed by dispersive elements and Fourier-transform methods to extract the absorption features over several tens of nm. However, so far comb-based absorption spectrometers have rested on conventional linear cavities and used only for gas spectroscopy.

In the following, we describe a novel method that extends the capabilities of a near-infrared optical frequency comb (OFC) to cavity ring-down evanescent-wave spectroscopy with a fiber loop [52]. The OFC teeth are kept resonant with the cavity modes using a Pound-Drever-Hall (PDH) locking scheme. Thanks to the strong group-velocity dispersion in the fiber, the loop cavity behaves as a highly dispersive element allowing only a narrow interval of the OFC wavelengths to be resonant with the cavity. A fast step scan of the repetition rate permits covering the whole comb emission range and thus performing fiber-optic cavity comb spectroscopy (FOCCS) on the broad absorption features of liquid samples. Using a spectrally-broadened output of the comb laser, obtained by extension of the original Er-fiber fs-pulsed laser using a nonlinear optical fiber, one octave of the near-IR can be spanned, from 1.05 to 2.1 micron.

The experimental setup is shown in Fig. (**9**). The sensing element, an evanescent-field access block (EAB), consists of a side-polished single-mode optical fiber that allows interaction of the cavity evanescent field with a liquid sample. A 20-m fiber-loop cavity is built around the EAB. Light from a mode-locked erbium-fiber laser comb is injected into the cavity and collected through 0.6-% evanescent fiber couplers. The system is all-fiber made without any free-space gap.

To make the OFC resonant with the fiber loop, the repetition rate is tuned in order to match a *magic condition* [55] for our cavity, which is achieved when the comb teeth spacing is an integer multiple of the cavity FSR for a given wavelength. However, the fiber cavity acts as a dispersive element, which selects a narrow group of teeth that obey the above mentioned matching condition. At other wavelengths, the magic condition is satisfied by a slightly different repetition rate.

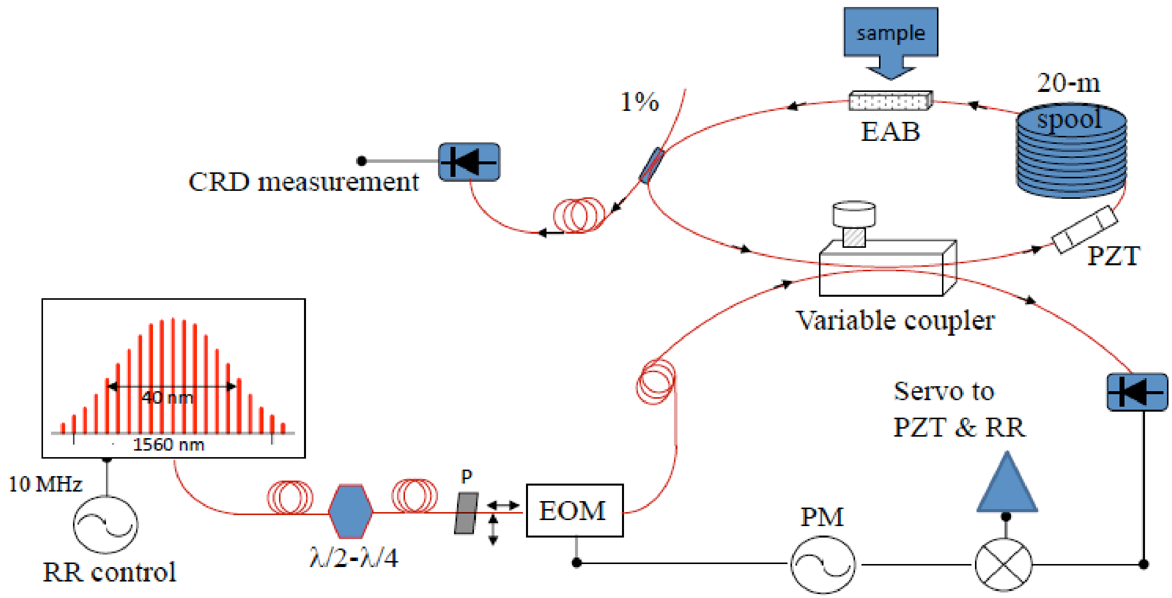

Fig. (9). Evanescent-wave liquid spectroscometer based on optical combs injected in fibre-optic ring cavities. RR: repetition rate; PM: phase modulation; PZT: piezoelectric transducer; EOM: electrooptic modulator; EAB: Evanescent field access block.

The central resonant wavelength is then swept by tuning the repetition rate synthesizer, thereby operating the cavity as a tunable spectrometer. Besides the fundamental magic condition (FMC) at 1550 nm, having a full width at half maximum (FWHM) of 0.7 nm (~ 250 teeth), there is a large population of narrower secondary magic conditions (SMCs) at different wavelengths. In principle, these extra resonances can be attributed to group velocity dispersion (GVD) of the fiber acting on the OFC pulse. Actually, only the teeth included in the thin spectral slice selected by the FMC are effectively coupled to the cavity and can be used for ring-down spectroscopy. Due to the presence of SMCs, the OFC cannot be completely switched off when modulating the total incident light power as in previous systems [46, 51, 52]. This problem is overcome by switching off only the FMC by deep amplitude modulation of PDH sidebands [56]. This process steals very rapidly the optical power from the frequency-locked comb carriers and effectively switch the cavity injection off.

From 100 repeated ring-down measurements in the same experimental conditions, a mean ring-down time $\tau = 3.04$ µs with a standard error of 0.004 µs (standard deviation divided by the square root of the number of samples) was obtained. Using this value, it is possible to estimate a minimum detectable single-pass absorbance of 3×10^{-5} for each spectral point, i.e. 1×10^{-6} $Hz^{-1/2}$ considering an effective detection bandwidth of $\frac{1}{2\pi\tau N} \approx 524$ Hz (N number of averaged acquisitions) [56]. This figure of merit surpasses the sensitivity levels reported in similar fiber-cavity systems [46, 48-50] and translates into a noise-equivalent absorption coefficient of 3×10^{-4} $cm^{-1}/\sqrt{Hz}$ per spectral point, considering the effective evanescent-wave interaction length of the sensor head (~ 30 µm). In addition, thanks to the spectrally-extended OFC emission, the sensor is capable of providing also information on the absorption spectrum over a wide wavelength range.

The spectroscopic performance is assessed by a test experiment with liquid samples containing polyamines, which exhibit strong absorption bands in the near infrared due to overtone vibrations [56]. All the samples are diluted with heavy water. During repetition rate steps, the fiber cavity remains locked to the OFC teeth while a LabView™ code controls both the radio frequency synthesizer that rules the repetition rate frequency for fine tuning of the FMC and the PDH signal to ensure a correct frequency-lock operation. Simultaneously, it acquires intracavity power data and performs ring-down time retrieval for each point of the FDS wavelength scan. Each value results from the average of the fitting parameters of 100 decay events. A full spectrum can be recorded in about 120 s. This limit is set by the GPIB communication channel between the computer and the oscilloscope for spectra acquisition but it can be pushed much further using a fast DAQ board. In Fig. (**10**), we show CRDS measurements along a fast scan of the FDS around an absorption band of tetra-ethylenepentamine (TEPA) using the direct Er-laser comb emission in the telecom range [29]. The result is in good qualitative agreement with an FTIR spectroscopic database [57] although these recordings were obtained with a drop of solution prepared from TEPA in D_2O at volume concentrations varying around 90 %. Furthermore, the spectrally extended emission of the OFC source was used to prove that our system is able to probe wide-band absorption of liquid species. Absorbance of a liquid ethylene diamine (EDA) sample in water was also obtained by the evanescent-wave cavity ring-down spectrometer over a 160-nm range as shown in Fig. (**11**) [56]. As opposed to other comb-based systems [10, 11], where dispersion causes strong bandwidth limitations, here GVD effects due to the intra-cavity fiber can be exploited for direct analysis of cavity spectra, without using any additional optical compensation element. Different sensing configurations can be considered using the same experimental scheme. Special engineered fibers may be adopted to replace the evanescent-field access element for

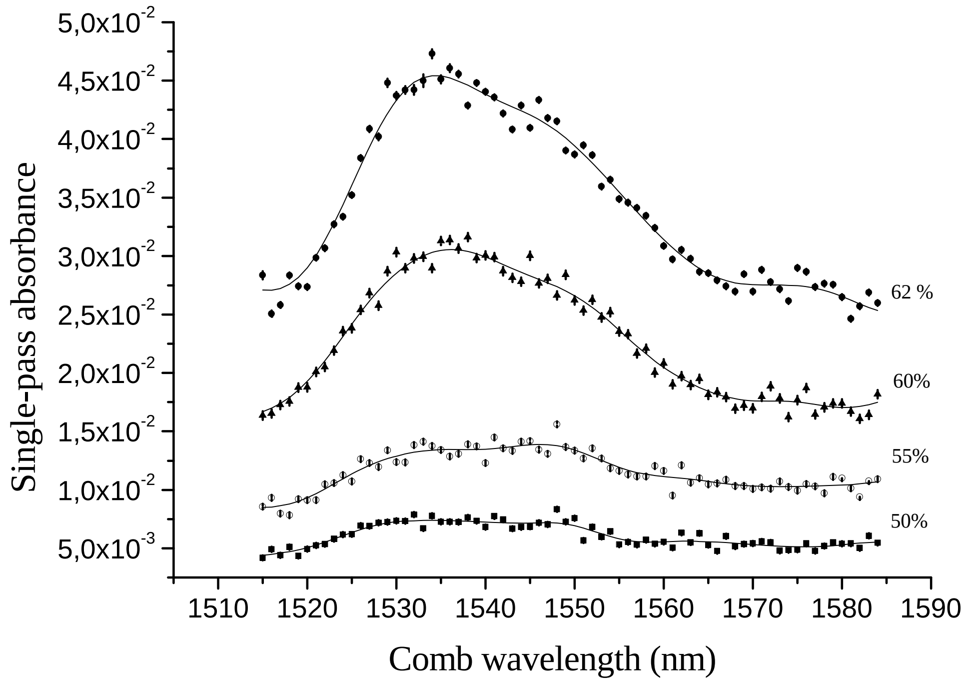

Fig. (10). Evanescent-wave absorption spectrum of a liquid sample containing tetraethylenepentamine (TEPA) diluted in D_2O at different concentrations (from 50 to 62 %).

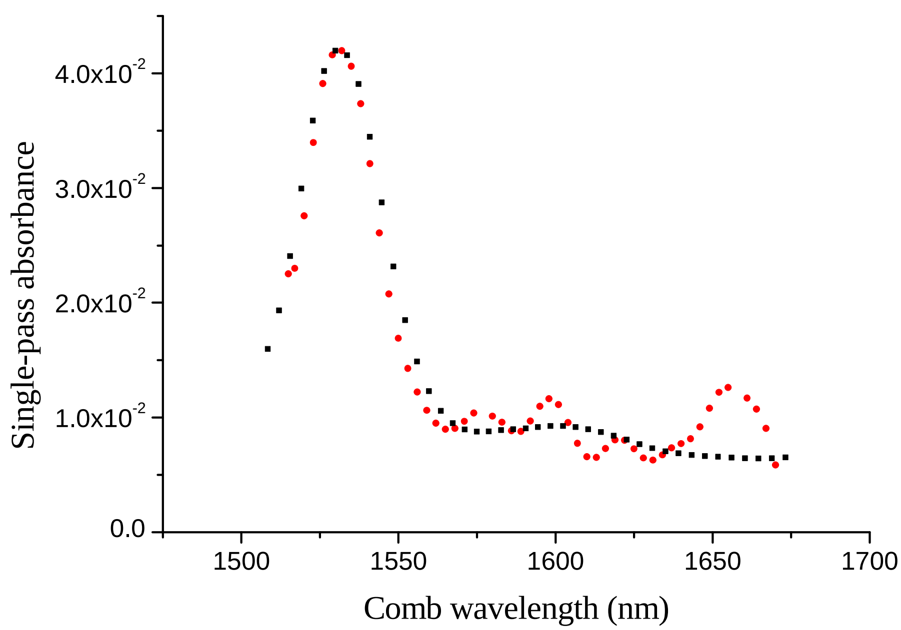

Fig. (11). Cavity ring-down absorption signals of a 90-% EDA sample in water (red dots) observed with the spectrally extended comb emission along a wide repetition rate sweep (spectral resolution ~ 3 nm). An FTIR spectrum with similar resolution is plotted for comparison (black squares). (Reprinted with permission from ref. 56. Copyright 2013, AIP Publishing LLC).

amplifying light-matter interaction and to optimize the spectroscopic performance also by tailoring cavity dispersion.

CONCLUSIONS

We have presented an overview of recently-developed optical-fiber cavity-enhanced systems aimed at mechanical, acoustic, inertial and chemical sensing using single-frequency lasers and broadband unconventional sources. High finesse cavities are nowadays technologically feasible with relatively-simple optical fiber devices. On the other hand, working in the telecommunication wavelength window provides enormous advantages in terms of quality to cost ratio. Moreover, using optical techniques derived from laser spectroscopy, noise reduction and real-time tracking of the fiber sensors are possible. Mode-locked laser comb synthesizers are also considered for their metrological performance as secondary optical-frequency references as well as their unique features as broad-spectrum, coherent radiation sources in the near-infrared.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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