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Mode matching of a laser-beam to a compact high finesse bow-tie optical cavity for quartz enhanced photoacoustic gas sensing

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ABSTRACT

We report on the optical characterization of a compact bow-tie cavity composed of two flat mirrors and two concave mirrors, all having a reflectance > 99.99% in the spectral range between 4.8 μm and 5.3 μm, mounted in a stainless-steel enclosure. The cavity was designed for the implementation of an intracavity-quartz enhanced photoacoustic sensor system. The propagation parameters of the intra-cavity beam were determined using the ABCD-matrix method, allowing the analytical formulation of the size of two beam waists occurring inside the cavity. A collimated mid-infrared laser beam was optically coupled and mode matched into the bow-tie cavity via a focusing lens. A cavity finesse of ∼2000 was measured at a pressure of 90 Torr inside the cavity, corresponding to an optical power enhancement factor of ∼320.

1. Introduction

The development of high reflectivity mirrors allows the use of multi-mirror resonators in various configurations for several applications [1]. One of these configurations is the symmetrical bow-tie resonator system, which consists of two concave mirrors and two plane mirrors. With respect to the linear cavity, a bow-tie configuration suffers higher intra-cavity losses (due to an increased number of high-reflectivity surfaces per round trip), requires more space and suffers astigmatic effects (because the two curved mirrors reflect the beam at an angle different from zero respect to the normal direction). However, bow-tie cavities offer also distinct advantages: i) more possible configurations for injecting (collecting) the optical field into (from) the cavity; ii) the input beam is reflected at an angle that prevents its re-entering into the laser thus avoiding the use of a costly optical isolator; iii) they are characterized by two cavity waists, one between the two curved mirrors and another between the two flat mirrors, which is larger than first waist [2]. Bow-tie resonators are used in many laser-based systems, such as diode end-pumped lasers and for the coupling of Gaussian beams into passive resonators with intra-cavity nonlinear devices [3–5]. Recently, a high-finesse optical cavity platform was combined for the first time with a quartz-enhanced photoacoustic (QEPAS) module for the realization of a novel method for trace gas sensing called intracavity-QEPAS (I-QEPAS) [6–8]. The I-QEPAS system was operated at a laser wavelength of 4.3 μm for CO_2 detection. A comparison with standard QEPAS performed under the same experimental conditions demonstrated that the I-QEPAS sensitivity scales with the intracavity laser power enhancement-factor [7]. In the first I-QEPAS demonstration, a symmetrical bow-tie resonator system configuration was implemented. The quartz tuning fork (QTF) was positioned at the cavity waist between the two concave mirrors.

A multi-mirror resonator can theoretically be treated in terms of the ABCD-matrix method [9–11]. The ABCD-matrix analysis is a general method used to calculate the transformation of the *q*-parameter (the complex radius) of a Gaussian beam through cascading optical elements, separated by fixed distances in order to form an optical resonator.

In this work, we applied the ABCD-matrix method to derive analytical expressions for the size of the two beam waists occurring inside a bow-tie cavity designed to be implemented for I-QEPAS sensing at 5.26 μm for NO detection [12,13]. We used these theoretical estimations to investigate the mode matching of a collimated laser beam to the bow-tie cavity by means of a coupling lens. Based on these results, we realized a compact bow-tie cavity composed by four mirrors mounted in a stainless-steel housing and investigated the mode matching between a mid-infrared laser beam at 5.26 μm and the cavity. A study of the cavity transmission peaks allowed measurements of the main characteristics of the cavity: the finesse,

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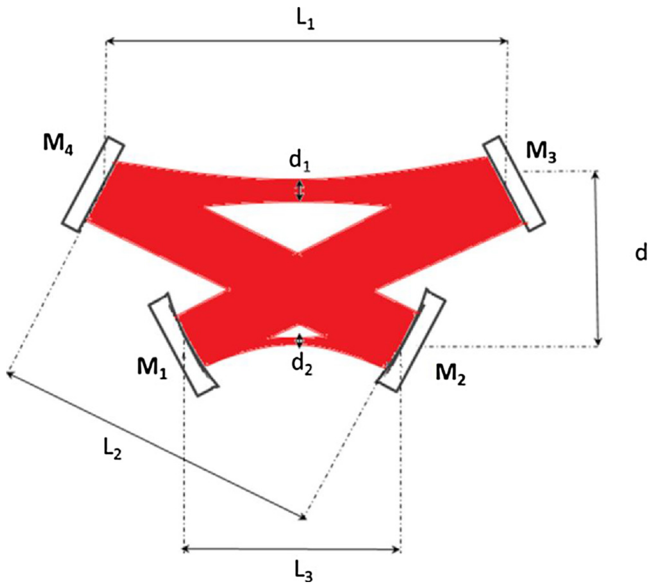

Fig. 1. The bow-tie resonator geometry employed in the reported study. The plane mirrors are separated by a distance L_1. The distances between M_1 and M_3 and M_2 and M_4 are identical and denoted as L_2. The spacing between the two concave mirrors M_1 and M_2 is denoted as L_3. The width of the cavity is denoted as d.

the width of the cavity mode and the power enhancement factor for two different gas pressure conditions.

2. Theoretical description of a bow-tie cavity

The schematic of the bow-tie cavity is depicted in Fig. 1.

The bow-tie resonator geometry has a symmetric configuration and consists of two concave mirrors M_1 and M_2 with a radius of curvature of R = 30 mm and two plane mirrors M_1 and M_2. L_1 = 31 mm, L_2 = 47 mm and L_3 = 56 mm are the distances between each mirror, giving a total cavity length of L = 181 mm. The width of the cavity d was chosen to reduce the optical aberrations and making the cavity also compact. The outcome of such a design results in a folding angle for each mirror of 11°. For the case of resonators consisting of spherical or planar mirrors, the cavity modes can be described by Hermite-Gaussian beams. Perfect optical coupling occurs when the lowest Hermite-Gaussian mode (TEM_{00} mode, hereinafter referred to as the fundamental mode) propagates into the cavity. High-order transverse modes occur when the mode matching is poor. The properties and the parameters of a Hermite-Gaussian beam propagation through an optical cavity can be analysed with the ABCD laws formalism. The analysis is based on the complex Gaussian beam q-parameter of the cavity, which contains information about the wavefront curvature R_c (the real part of q) and the Rayleigh range (the imaginary part of q). The result is Eq. (1):

$$\frac{1}{q} = \frac{1}{R_c} - j\frac{\lambda}{\pi(w)^2} \quad (1)$$

where w is the radial size of the beam and λ is the light wavelength. It can be shown that the bow-tie cavity generates two beam-waists w_1 and w_2, positioned between the two flat mirrors M_3 and M_4 and the two concave mirrors M_1 and M_2, respectively [2]. At these points, the characteristic transverse dimension of the electric field shows a minimum and the radius of curvature of the wavefront is infinite. For the fundamental cavity the eigen-mode q_1-parameter, the ABCD paraxial propagation matrix for a complete round-trip, starting from the intracavity focus with beam waist size w_1, results in Eq. (2):

$$\begin{pmatrix} A_1 & B_1 \\ C_1 & D_1 \end{pmatrix} = \begin{pmatrix} 1 & \frac{L_1}{2} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{2}{R} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_3 + 2L_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{2}{R} & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{L_1}{2} \\ 0 & 1 \end{pmatrix} \quad (2)$$

For a complete round-trip, starting from the focus with a beam waist size w_2 between the two plane mirrors, the ABCD matrix for the q_2-parameter results in Eq. (3):

$$\begin{pmatrix} A_2 & B_2 \\ C_2 & D_2 \end{pmatrix} = \begin{pmatrix} 1 & L_2 + \frac{L_3}{2} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{2}{R} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{2}{R} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_2 + \frac{L_3}{2} \\ 0 & 1 \end{pmatrix} \quad (3)$$

From Eqs. (2) and (3), results $A_1 = A_2 = D_1 = D_2 = -0.786$, $B_1 = -0.714$, $C_1 = 0.535$, $B_2 = -107.515$ and $C_2 = 0.004$. The q_i-parameter for the TEM_{00} mode of the cavity at the two beam waists is found from the self-consistency relationship by forcing q_i to transform into itself after a cavity round trip:

$$q_i = \frac{A_i q_i + B_i}{C_i q_i + D_i} \quad (4)$$

with i = 1 or 2. By using the relations $A_iD_i - B_iC_i = 1$ and $A_i = D_i$, the solution of the self-consistency equation is given by Eq. (5):

$$\frac{1}{q_i} = -\frac{A_i - D_i}{2B_i} - j\frac{\sqrt{1 - A_i^2}}{B} \quad (5)$$

At the two beam waists, the radius of curvature is infinite, so that the related q_i-parameters are:

$$\frac{1}{q_i} = -j\frac{\sqrt{1 - A_i^2}}{B} = -j\frac{\lambda}{\pi(2w_i)^2} \quad (6)$$

Hence, the sizes of the beam at two waists defined as $d_i = 2w_i$ are given by:

$$d_i = \sqrt{\frac{\lambda B_i}{\pi\sqrt{1 - A_i^2}}} \quad (7)$$

Once the cavity parameters are known, the laser can be mode matched to the cavity. Theoretically, the radius and wavefront curvature of the incident laser beam must match those of a mode of the cavity in order to have perfect mode matching. If the laser source and the cavity resonator are in fixed positions, the mode matching condition can be realized by employing a focusing lens [14]. Both the focal length and the position of the lens between the laser and optical cavity must be selected in order to provide a position and size of the waist matching as much as possible that is defined by the cavity q-parameter. If the waist size and position of the input beam are different from those of the cavity, higher-order transverse modes are excited [15]. Hence, the larger is the misalignment from mode matching condition, the larger is the intensity and number of higher-order modes that are excited. The high-order spatial modes can be characterized by non-degenerate resonant frequencies differing from the fundamental mode.

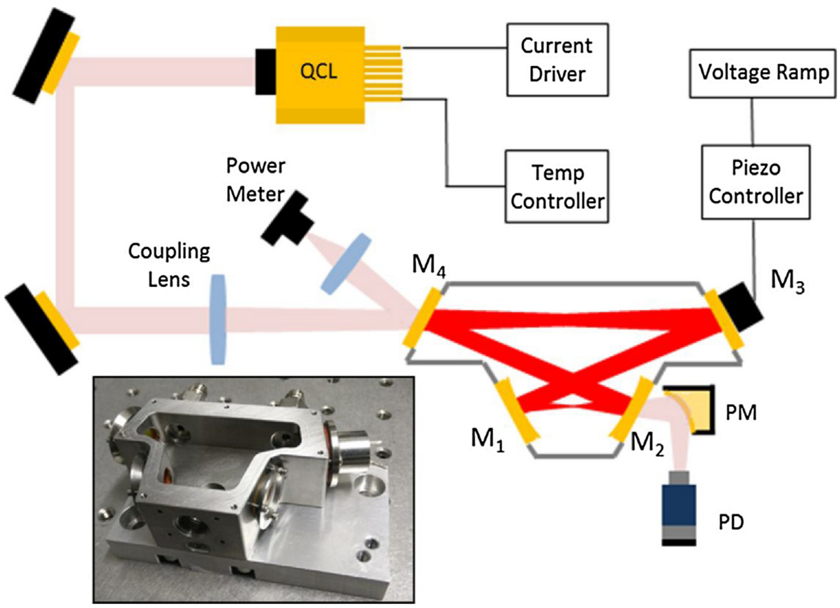

Fig. 2. Schematic of the experimental setup employed for coupling a collimated laser beam into the bow-tie cavity. Inset: a picture of the stainless-steel housing containing the four mirrors forming the bow-tie cavity. QCL – Quantum cascade laser. PM – Parabolic Mirror. PD – Pyroelectric Detector.

3. Experimental setup for the mode-matching

A sketch of the experimental setup for the study of the optical characteristics of the cavity is shown in Fig. 2.

A continuous-wave DFB quantum cascade laser (Hamamatsu Photonics) emitting at 5.26 μm (with a current of 580 mA at a temperature of 10 °C) was used as the laser source to be coupled with the bow-tie cavity. The temperature was stabilized by means of a temperature controller and a low-noise current driver (QCL1000, Wavelength Electronics) in order to reduce the spectral broadening of the laser line induced by QCL current noise. The laser beam was collimated by using an aspheric lens with a focal length of 6.0 mm. Two mirrors were used in order to guide the collimated laser beam to the coupling lens. The bow-tie cavity consists of four mirrors, as schematically shown in Fig. 1, placed in a stainless-steel housing to create a compact and portable optical cavity. M_1, M_2 and M_4 are mounted by means of O-rings, which were fixed to the housing by means of steel rings, each one supported by three screws (as shown in the inset of Fig. 2). Adjustments on the screws allow fine tilting of the mirrors for the alignment of the optical cavity. O-rings ensure a vacuum seal for operation at reduced pressures. The piezoelectric stack was glued to the housing to ensure the vacuum seal. All ZnSe mirrors that compose the bow-tie cavity were realized by Lohnstar Optics, Inc. and have a reflectance >99.99% in the spectral range between 4.8 μm and 5.3 μm on one side and an anti-reflection coating at the same wavelength range on the other side (the plano-side for M_3 and M_4). In Fig. 3 we reported the reflectance of the mirrors composing the cavity provided by the manufacturer.

All mirrors have high transmittance at ~632 nm, for alignment purposes using a He-Ne laser (which is not shown in Fig. 2). M_2 was mounted on a piezoelectric stack (PK2FMP2, Thorlabs) driven by a high voltage piezo-controller and providing precise tuning of the cavity length over a few microns range. By using Eq. (7), we determined that for a laser wavelength of $\lambda = 5.26$ μm, the beam sizes at the two waists are: $d_1 = 44$ μm and $d_2 = 539$ μm.

A detailed analysis of the laser beam profile is needed to determine whether M_1 or M_4 should be used as the input mirror for the best optical coupling with the laser beam. The laser beam profile at the mode matching lens position was measured using a pyrocamera (Pyrocam III, Ophir Spiricon, 124 × 124 pixels, pixel size 85 μm). To measure the beam size, we employed the second-order moment of the beam intensity distribution *I(x,y)*, which is a measure of the variance of the 2D-intensity profile at the origin for both directions *x* and *y* [16]. We obtained $d_x = 2.05$ mm and $d_y = 1.95$ mm. The spot sizes in *x,y* directions at the focal point provided by a lens having a focal length *f* and a radius of curvature *R* can be estimated by the following equation [17]:

$$2w_{x,y} = \frac{d_{x,y}}{\sqrt{1 + \left(\frac{\pi d_{x,y}^2}{4\lambda R}\right)^2}} \tag{8}$$

Values of $w_{x,y}$ matching d_2 (539 μm) can be obtained by using a coupling lens having a focal length of 15 cm. The beam size d_1 could be matched either by using a focal length of 1.5 cm (which is not feasible because the numerical aperture would be too large), or by using a long focal length and strongly reducing the collimated beam size by means of a pinhole (which would reduce the optical power to be coupled into the cavity). Hence, the best coupling conditions can be achieved only by selecting M_4 as the cavity input mirror. To determine the best operating conditions, we compared the results obtained using two different coupling lenses having focal lengths $f = 15$ cm and f = 10 cm. Although theoretically better results are expected if a lens with $f = 15$ cm is used, we observed a more efficient optical coupling if a lens with $f = 10$ cm is used. This discrepancy can be ascribed to a distortion effect of the input mirror M_1 on the focusing beam, thereby requiring the use of a lens with a shorter focal length. For this reason, we found the best conditions were obtained by using a 1 inch-diameter ZnSe lens with $f = 100$ mm and $R = 140.5$ mm (which corresponds to $w_x = 448$ μm and $w_y = 468$ μm at $\lambda = 5.26$ μm).

The mode-matching lens was mounted in a cage system, which allows fine adjustments of the distance between the lens and M_4. A 90° off-axis gold coated parabolic mirror with a reflected focal length of 15 mm and a diameter of 0.5 inch (MPD00M9-M01, Thorlabs) was used to focus the radiation exiting from M_2 to a pyroelectric detector PD (PVI-4TE, Vigo System). A voltage ramp at a frequency of 10 Hz applied to the piezo controller moves M_2 back and forth and thereby periodically changes the resonator length. A power meter was used to measure the optical power reflected by the input mirror M_4.

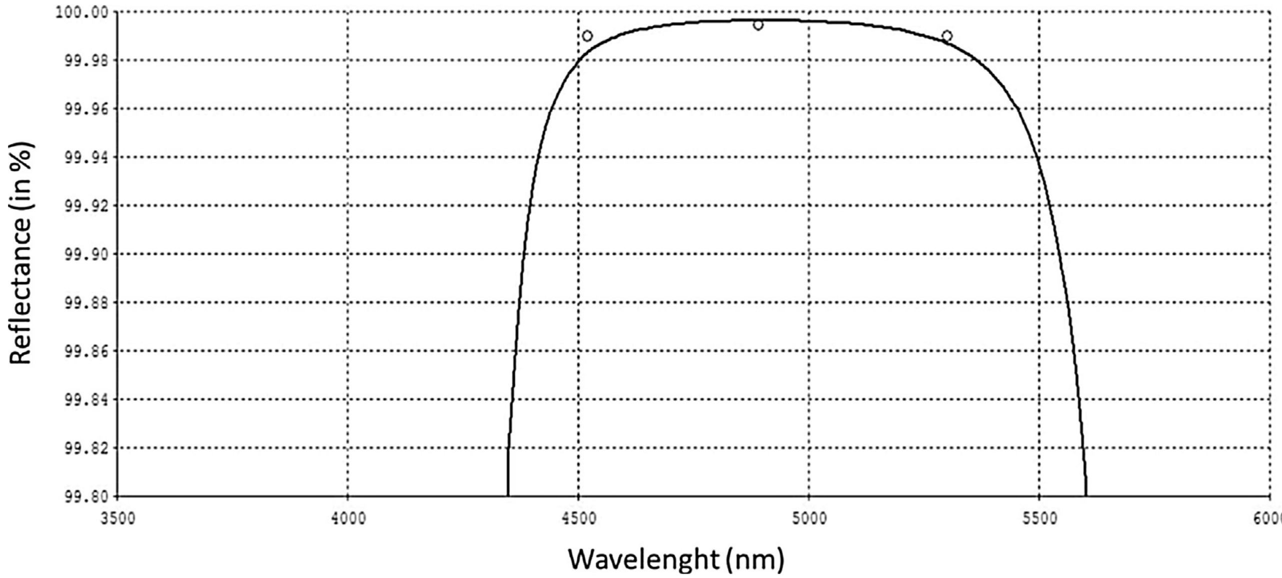

Fig. 3. Mirror reflectance spectrum provided by Lohnstar, Optics Inc. in the range between 3.5 μm and 6.0 μm. The three dots are located at 4520 nm, 4890 nm and 5300 nm corresponding to a reflectivity of 99.99%, 99.995% and 99.99%, respectively.

4. Transmission peaks of the cavity

By applying a voltage ramp to the piezo controller, each time the laser frequency matches the frequency of a cavity mode, peaks in cavity transmission are measured using the Pyroelectric Detector (PD) and sending its signal to an oscilloscope. Since the laser beam is not perfectly aligned and mode-matched to the external cavity ($w_{x,y<}$ d_2), high order transverse modes of the optical cavity are expected in the PD signal. Fine adjustment of the position of both the mode matching lens and of the angular displacement of cavity mirrors allow investigating how mode matching affects the observed transmitted modes. The alignment is optimized by minimizing the intensity of higher order modes and maximizing the optical power coupled into the fundamental mode. By adjusting the voltage scan range of the piezo controller, it is possible to cover one free spectral range (FSR) of the cavity and observe two resonant transmitted peaks. In Fig. 4a the transmission peaks of the cavity are depicted, that occur as a result of changing the length of the cavity by one FSR and keeping an air sample inside the cavity at atmospheric pressure. Fig. 4b shows an enlarged view of one of the cavity peaks and its Lorentzian lineshape demonstrates the achievement of a low loss condition. By measuring the cavity peak full width at half-maximum $\Delta\nu_{FWHM}$, it is possible to extract the cavity finesse parameter *F*, defined as the ratio $F = FSR/\Delta\nu_{FWHM}$.

To investigate the effect of gas pressure, we reduced the air pressure inside the compact bow-tie cavity to 90 Torr. The observed transmission peaks related to one free spectral range are shown in Fig. 5.

To verify that the cavity the cavity is operating in steady state, the piezo-actuator was scanned at a lower frequency (1 Hz) and a finesse of the cavity very similar with that measured at 10 Hz was determined. Since the free spectral range is given by the speed of light *c* divided by the round-trip path length *L* (in our case FSR = c/L = 1.66 GHz), this value was used to convert the x-axis from time-unit to frequency-unit. In Table 1, we summarized the main parameters of the cavity extracted from the peak features at the two investigated pressures:

When intra-cavity losses increase, the width of the resonance is also affected. At atmospheric pressure, air absorption within the cavity light path [18–20] strongly contributes to the cavity losses per round trip and as consequence the transmission peak is affected. The power enhancement factor is defined as [21]:

Table 1
Summary of the main characteristics of the cavity measured starting from the transmission signal of the cavity: the cavity finesse *F*, the width of the cavity mode and the power enhancement factor *G*, at atmospheric pressure and 90 Torr.

	Atmospheric Pressure	P = 90 Torr
Finesse (*F*)	1812	1989
Peak FWHM ($\Delta\nu_{FWHM}$)	915 kHz	833 kHz
Power enhancement factor (*G*)	288	317

$$G = \frac{F}{2\pi} \tag{9}$$

Values of G of ~ 320 are reached, 35% higher than the value obtained in the bow-tie cavity implemented in the first I-QEPAS system demonstration [7]. Eq. (9) can be used to estimate the optical power inside the cavity only in case of perfect impedance matching. However, this condition is hard to be reached when operating with QCLs due to input mirror transmission losses. Since the QCL linewidth (from few MHz to tens of MHz [22]) are larger than the cavity linewidth (<1 MHz) only a fraction of the QCL power can be coupled into the cavity. Therefore, we introduced an optical coupling efficiency factor η, defined as the ratio between the optical power incident on mirror M_4 and that reflected by M_4, for a correct estimation of the real intra-cavity power enhancement factor. When the cavity length is not matched with the laser mode, the power meter measured a constant power value I_0. Once the cavity length matches the laser resonance, a drop I_1 in the power meter signal is observed. The power coupling efficiency, i.e. the fraction of the QCL power coupled into the cavity, is measured as $\eta = 1 - I_1/I_0$. We extracted an optical coupling efficiency of η = 0.2 and by considering a laser power of P = 108 mW measured after the coupling lens and the intra-cavity optical power results:

$$P_c = \eta PG \tag{10}$$

which leads to 6.2 W at atmospheric pressure and an increase to 6.8 W at 90 Torr.

The bow-tie cavity was designed to be implemented in an intra-cavity QEPAS (I-QEPAS) for the detection of the NO absorption line at 5.26 μm. A detection sensitivity of 4.9 parts-per-billion in volume was previously achieved with a standard QEPAS sensor

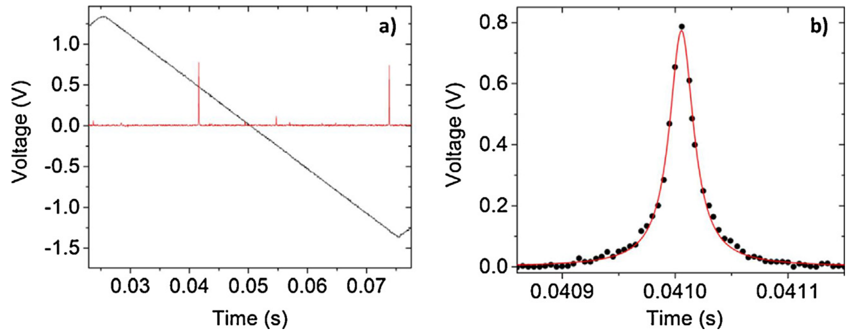

Fig. 4. (**a**) The cavity transmission signal obtained at atmospheric pressure (red solid line) when a voltage ramp (black solid line) is applied to the piezo controller in order to cover one free spectral range of the cavity; (**b**) Enlarged view of one of the transmission peaks of the cavity (black dots) and related Lorentzian best fit (red solid line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

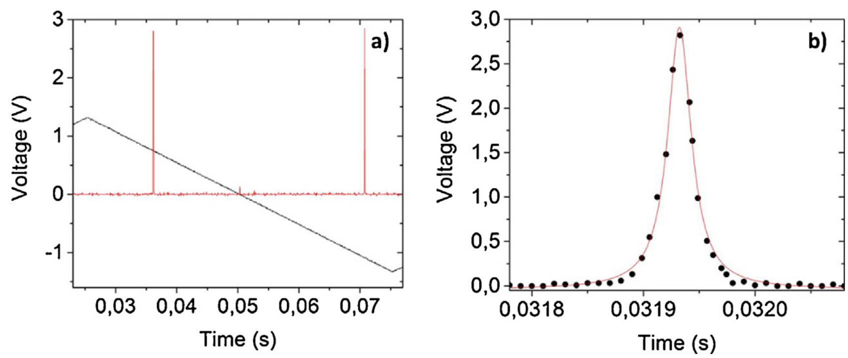

Fig. 5. (**a**) Transmission of the bow-tie optical cavity containing air sample at 90 Torr (red solid line) and the voltage ramp (black solid line) applied to the piezo controller; (**b**) Enlarged view of one of the cavity transmission peaks (black dots) and the related Lorentzian fit (red solid line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

system operating at 5.26 μm with an optical excitation power of 66 mW [12,13]. Since the QEPAS signal scales linearly with optical power and considering an intra-cavity optical power of 6.8 W, a record NO detection limit of ~ few tens of parts-per trillion could be reached implementing the bow-tie cavity in combination with a QEPAS system acoustic detection module. Further improvements could be obtained by implementing custom-made QTFs with optimized sensing performance and prong spacing larger enough, with respect to the selected cavity beam waist, to avoid QTF illumination by the propagating laser beam [23]. Employing QTFs with a prong spacing larger than 700 μm could be placed between the two plane mirrors M_3 and M_4. With respect to the standard QTF, an easier alignment and a reduction of the optical noise is expected [24]. The I-QEPAS sensor to be realized will potentially allow the realization of a compact, portable and high-sensitive device suitable for real time and in-situ applications, such as environmental monitoring and medical diagnostics of human diseases (e.g. exhaled breath analysis).

5. Conclusions

In this work, we designed and realized a compact and portable bow-tie optical cavity assembled in a stainless-steel housing aimed at I-QEPAS sensing applications. A focusing lens was used to couple a collimated mid-infrared laser beam into the bow-tie cavity by using one of two flat mirrors as the input mirror. By analyzing the transmission peaks of the cavity, we estimated a finesse of 2000 and an optical power enhancement factor of 320, when the pressure is reduced to 90 Torr. The next step will be the implementation of the realized cavity in an I-QEPAS setup for sensitive and selective NO detection.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgments

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Biographies

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