

Non-resonant wavelength modulation saturation spectroscopy in acetylene-filled hollow-core photonic bandgap fibres applied to modulation-free laser diode stabilisation

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Abstract: In this paper the application of Wavelength Modulation (WM) techniques to non-resonant saturation spectroscopy in acetylene-filled Hollow-Core Photonic Bandgap Fibres (HC-PBFs) and modulation-free Laser Diode (LD) frequency stabilisation is investigated. In the first part WM techniques are applied to non-resonant pump-probe saturation of acetylene overtone rotational transitions in a HC-PBF. A high-power DFB chip-on-carrier mounted LD is used in conjunction with a tuneable External Cavity Laser (ECL) and the main saturation parameters are characterized. In the second part a novel feedback system to stabilize the DFB emission wavelength based on the WM saturation results is implemented. Modulation-free locking of the DFB laser frequency to the narrow linewidth saturation feature is achieved for both constant and variable LD temperatures.

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Introduction

During the last decade the application of Photonic Bandgap Fibres (PBF) [1,2] to nonlinear optics has achieved major progress and is a very active and promising physics research field [3]. In particular, the application of HC-PBFs to gas sensing [4–6] has been extended to non-linear absorption regimes and saturation spectroscopy of several gas species has been investigated in these microstructures [7,8]. Application to wavelength referencing and integration of PBF fibres into portable systems has been studied and demonstrated [9–12], together with characterization of the absorption properties of specific gases, such as acetylene, in the 1.5 μm spectral region [13–15]. The optical pump power and pressure dependence of

the linewidth of saturated acetylene transitions, together with the effect of the fibre geometry, have been studied in both resonant and non-resonant pump-probe experiments [16–19]. In order to further improve the accuracy of absolute wavelength references, several laser locking techniques based on saturation effects have been investigated, typically involving a pump-probe scheme where the high pump power is achieved by means of an Erbium-Doped Fibre Amplifier (EDFA) and part or all of the pump laser light is modulated. Some examples include stabilisation of External Cavity Lasers (ECL) using piezo-locking in acetylene-filled Fabry-Perot cavities [20,21] or Rubidium saturation spectrometers [22], ECL locking in Rubidium and metastable Argon reference cells using differencing techniques [23], Distributed Feedback (DFB) laser stabilisation using third-harmonic techniques [24,25] and modulation transfer spectroscopy [26] in acetylene gas cells, or recent experiments where large-core HC-PBFs have been used in conjunction with Frequency Modulation (FM) techniques to stabilize fibre lasers [27,28]. Each of these techniques has strengths and weaknesses and can be selected depending on the particular application to be used.

In this paper a novel application of WM techniques [29] to modulation-free laser stabilisation is presented, using non-resonant saturated transitions of acetylene in HC-PBFs. WM techniques are widely spread and well-known detection techniques used in laser spectroscopy to enhance the achievable sensitivity for a given sensing experiment. Modulation of the probe laser is used to produce an error signal to lock the pump, which in this case consists of a high-power DFB chip-on-carrier laser diode, the output from which is not split or modulated at any experimental stage. This is a novel feature as compared with other techniques, no EDFA is necessary to achieve saturation and the required locking electronics remain very basic. Frequency stabilisation is demonstrated for both constant and variable temperatures of the DFB laser but the technique remains valid for and can be extended to other types of laser sources.

Experiment description

A schematic of the pump-probe experimental set-up is shown in Fig. 1 below.

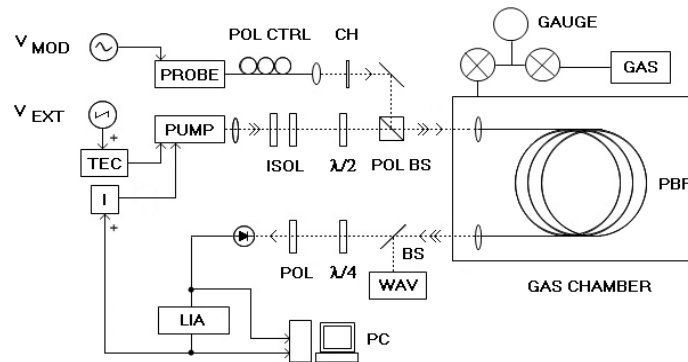


Fig. 1. Pump-probe and laser stabilisation experimental scheme. Main elements and abbreviations used: V_{MOD} = Modulation Voltage (wavelength modulation); V_{EXT} = External Voltage (temperature control); TEC = Thermo Electric Cooler; I = Current Source; PROBE = Probe laser; PUMP = Pump laser; POL CTRL = Polarization Controller; CH = Chopper; ISOL = Optical Isolator; $\lambda/2$ = Half-wave plate; POL BS = Polarizing Beam Splitter; PBF = Photonic Bandgap Fibre; BS = Beam Splitter; WAV = Wavemeter; $\lambda/4$ = Quarter-wave plate; POL = Polarizer; LIA = Lock-In Amplifier; PC = Personal Computer. All wavelength-dependent elements are designed at a working point of 1.5 μm . Amplitude modulation using a chopper and wavelength modulation of the probe laser are alternatively implemented during the experiment depending on the detection technique.

The probe laser is a commercial ECL system with a fiberized optical output that can be fine tuned between 1510 nm and 1590 nm with a resolution better than 1 MHz and power stability better than 1%, and also includes an external modulation facility. Depending on the

detection technique to be used, modulation is implemented either via an external signal or using a chopper. The pump source is a chip-on-carrier high-power Bookham DFB laser diode with a tuning range of approximately 1.5 nm around 1532.3 nm and a maximum optical output power in excess of 100 mW. It includes an integrated thermistor sensor and is mounted on a heat sink combined with a Peltier element, and operated using external current and temperature control units. The collimated laser emission is protected from back reflections by using two optical isolators in series, each carefully adjusted to maximise the transmission (greater than 98%) and minimise the feedback into the laser. The polarization of the probe and pump beams is adjusted using a polarization controller and $\lambda/4$ plate respectively. Polarizations are set to be linear and mutually orthogonal and both beams are combined using a polarizing beam splitter before coupling into the PBF. The PBF used in the experiment, a commercial model HC-1550-02 from Crystal Fibre A/S with a hollow core of approximately 11 μm in diameter [30], is placed inside a gas chamber connected to an acetylene ($^{12}\text{C}_2\text{H}_2$) cylinder and high-speed turbo-vacuum pump by means of vacuum/isolation valves. The pressure of $^{12}\text{C}_2\text{H}_2$ inside the main chamber is measured indirectly using a gauge that is placed in a subsidiary chamber of a known volume. Both laser outputs and the fibre input and output ends are placed on precision position stages so the coupling into and out of the fibre can be independently optimized. Wavelength can be measured with an accuracy of ± 1 pm while the probe and pump beams are separated using polarization-dependent components and detected with a InGaAs photodiode (PD). This photodiode signal is fed into a Lock-In Amplifier (LIA) operating at either the chopper or the probe modulation signal frequency depending on the detection technique to be used, and data acquired by means of a GPIB personal computer interface. A feedback loop is implemented when applying WM techniques where the LIA output is connected to the pump laser current source. Additional temperature control of the pump laser is achieved by means of an external voltage source connected to the thermoelectric cooler (TEC) unit.

Saturation of overtone rotational absorption transitions of $^{12}\text{C}_2\text{H}_2$ in PBFs employing a WM pump-probe technique

In the first part of this paper the saturation of $^{12}\text{C}_2\text{H}_2$ overtone rotational transitions in the $\nu_1 + \nu_3$ vibrational band around 1.5 μm is studied. Rotational absorption lines to the low-frequency side of the band centre ω_0 correspond to an increment of the rotational quantum number of $\Delta J = -1$ and are referred to as the *P branch*, while those to the high-frequency side with $\Delta J = +1$ form the *R branch* [31]. A non-resonant scheme is used with the pump laser diode targeting the P(13) gas line centred at 1532.830 nm and the probe wavelength tuning across the R(11) absorption feature at 1519.137 nm. This overtone rotational absorption scheme is essentially a three-level coupled system with a Λ -type $R(J-1) - P(J+1)$ interaction, where both transitions share the same upper energy level [16]. The output powers of the pump and probe lasers are approximately 100 mW and 5 mW respectively while the maximum measured coupling of both lasers into the PBF reaches approximately 50%. Final spatial separation of the beams is achieved by means of the polarization components already described. The probe beam is either modulated using a chopper when direct transmission is to be recorded or using an external signal when applying WM detection techniques. In that case the chopper is removed and the probe laser modulated sinusoidally at a frequency of $f = 2.430$ kHz, with the lock-in amplifier demodulating the detected signal at the first harmonic of the modulating frequency. The experiment was carried out at a room temperature of $T = 22^\circ\text{C}$ and the acetylene gas pressure in the measurement chamber was maintained at 1 mbar while the total pressure including the air present was 3 mbar.

The results for the saturation of the three-level system are presented in Fig. 2. Non-resonant saturation of the absorbing transition was achieved and is clearly depicted in the probe transmission spectrum shown in Fig. 2(a). For PBF input laser pump powers of around 40 mW, the measured Doppler width is $\Delta\nu_D \approx 470$ MHz and a saturation dip is created at the

absorption line centre with a measured depth and linewidth of typically 2% and 50 MHz respectively. The narrow measured linewidth of this saturation dip agrees well, within experimental error, with the estimated theoretical value of approximately $\Delta\nu_{\text{SAT}} \approx 65$ MHz. This value includes a Lorentzian collisional broadening contribution of $\Delta\nu_{\text{COL}} \approx 25$ MHz for a total pressure of 3 mbar [32] plus a transit-time broadening [33] of $\Delta\nu_{\text{TT}} \approx 40$ MHz. The assumption is made that acetylene molecules cross a Gaussian beam of 1/e intensity diameter $d = 7.5 \mu\text{m}$ with a 3D mean molecular velocity $v_{3\text{D}} = \sqrt{(8RT/\pi M)} = 490.3 \text{ ms}^{-1}$ at a temperature of $T = 22^\circ\text{C}$, and a corrected 2D velocity of $v_{2\text{D}} = \sqrt{(2/3)}v_{3\text{D}} = 400.3 \text{ m s}^{-1}$. The total linewidth of the saturation dip corresponds to the convolution of both effects and equals the sum of the two contributions if both lineshapes are Lorentzian [34]. However, the transit-time broadening follows a sinc-like lineshape [35] so an approximation has been introduced to estimate the total saturation dip linewidth. The estimated result agrees well with those obtained by R.Thapa et. al. [19], where acetylene saturated transitions were studied in HC-PBFs of different diameters for various pressure values. Transit-time broadening is commonly the limiting factor for the transition linewidth, and can be reduced to values of around ≈ 15 MHz by selecting low-velocity molecules (Hald et. al. [36],) or down to ≈ 10 MHz using large-core Kagome PBFs (Jones et. al. [27],). Pressure broadening can be minimized by working at low acetylene pressures and thus increase the saturation level achieved, as done in HC-PBFs by Benabid et. al. [16] for pressures as low as 0.001 mbar.

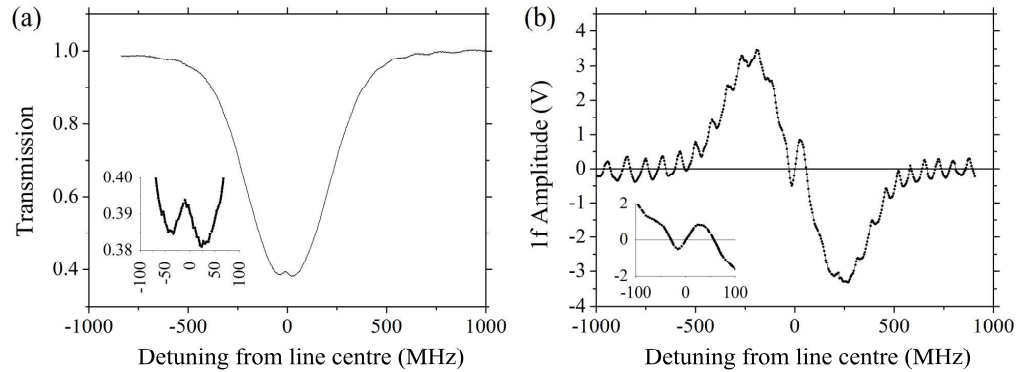


Fig. 2. (a) Non-resonant pump-probe saturation results for 1 mbar of acetylene inside the PBF at an input pump power of 40 mW. The measured Doppler width is $\Delta\nu_{\text{D}} \approx 470$ MHz while a saturation dip of around 2% with a linewidth of 50 MHz is observed at the centre of the probe transmission spectrum. No modulation is applied to the probe in this case. (b) First-harmonic (1f) WM signal of the saturated probe transmission spectrum. The 1f signature of the saturation dip can be clearly observed in the line centre, with an approximate width of 50 MHz peak-to-peak as measured and shown in the inset.

On the other hand WM detection results are presented in Fig. 2(b), where the first harmonic (1f) of the probe transmission spectrum includes the zero-crossing saturation dip signature at the line centre. The modulation depth of the probe laser is optimized to achieve the maximum amplitude of this narrow feature, which presents a measured peak-to-peak width of approximately $\Delta\nu_{\text{SAT}}^{\text{1f}} \approx 50$ MHz as clearly shown in the inset. This 1f signal is used as a feedback to implement the frequency stabilisation loop as described in the next section. Some existing schemes achieve error signals with peak-to-peak widths of ≈ 10 MHz (large core HC-PBFs, RF techniques [27]) or ≈ 700 kHz (ECL lasers and Fabry-Pèrot cavities [20],), but they usually require more complex experimental set-ups. Residual coupling reflections in the system together with transmission ripples in the PBF due to multimode propagation account for the observed periodic pattern in the background (with an equivalent etalon cavity length of $l \approx 1.6$ m).

Modulation-free DFB laser diode wavelength stabilisation

A modulation-free, novel technique to stabilize the emission wavelength of the pump DFB laser diode based on the previous WM saturation results is now described. As schematically shown in Fig. 1 the basic idea is to implement a feedback control loop [37] by connecting the LIA output back to the pump laser current control unit, with this output measurement $y(t)$ corresponding to the amplitude of the first-harmonic saturation dip at the line centre $y(t) = 1F(t)^{\text{SAT}}_C$. In the ideal case where the pump emission wavelength does not drift in time from the absorption line centre the saturated 1f signal reaches its zero crossing, so that the output fulfils the condition $y_{\text{IDEAL}}(t) = r(t) = 0$ defining the reference value $r(t)$ for the control loop. However, under normal operational conditions the emission wavelength of the chip-on-carrier DFB laser diode drifts in time due to temperature and current perturbations and a non-zero error signal $e(t) = y(t) - r(t) = y(t)$, $y(t) \neq 0$ is generated. In order to compensate for this drift the lock-in phase is set to provide negative gain so that a negative drift of the pump laser frequency $\Delta\nu_{\text{PUMP}} < 0$ corresponds to a positive output amplitude $y(t) > 0$ and vice versa. In this manner the frequency correction introduced by this simple loop counteracts the laser drift and the technique allows for the emission wavelength of the pump to be stabilized without any modulation applied to the laser diode. Note that any drift of the pump emission wavelength makes the *saturated* 1f feature to move across the *overall* probe 1f lineshape, so that the frequency locking interval is ultimately limited by the total width of the saturated 1f. On the other hand, any small drift of the set value for the modulated probe laser frequency is also effectively nullified by the locking loop.

Results for the successful implementation of this technique are presented in Fig. 3 below.

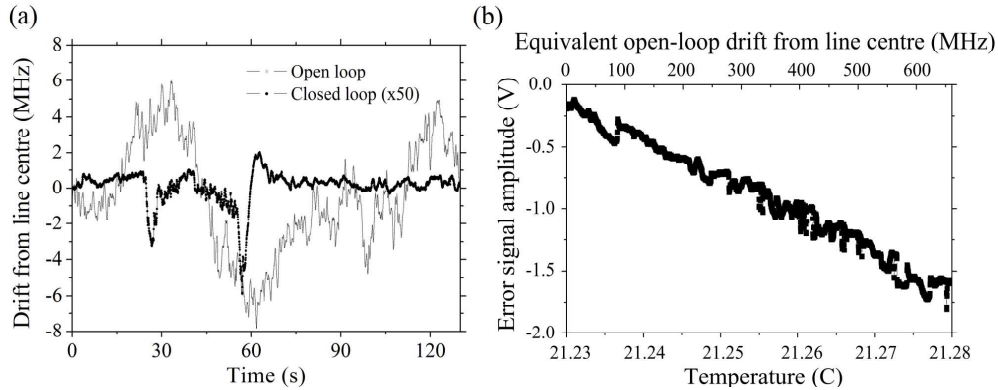


Fig. 3. (a) Comparison of pump laser emission frequency drift at constant laser temperature with and without implementation of a control loop. An open-loop drift in excess of 10 MHz is significantly reduced to a RMS value of 180 kHz around the gas line centre. Deliberate temperature perturbations are compensated for, as observed in the corresponding trace (scaled up by a factor of 50 for clarity). (b) Error signal amplitude as a function of pump laser temperature with the stabilisation loop implemented. The signal amplitude increases as the temperature is raised, thus compensating the external perturbation and stabilizing the laser emission wavelength. Stabilisation is achieved over a temperature interval of $\Delta T = 0.05^\circ\text{C}$, equivalent to an open-loop frequency drift in excess of 650 MHz as shown in the additional scale.

A comparison of the DFB laser diode typical frequency drift at a constant temperature of $T = 21.5^\circ\text{C}$ with and without a feedback control loop is first presented in Fig. 3(a). The DFB wavelength drift in time without any control loop is measured by coupling the laser beam into a single mode fibre and sending it to a calibrated gas cell containing 5 mbar of acetylene at a total gas pressure of 10 mbar. The laser emission wavelength is set at the acetylene P(13) absorption line centre and the diode is externally modulated at a frequency of $f = 2.4$ kHz in order to apply WM detection techniques. The amplitude of the 1f trace at the line centre is

then recorded in time, being directly proportional to the laser wavelength drift and insensitive to any coupling induced power change. Typical DFB laser drifts of more than 10 MHz are measured as observed in Fig. 3(a) and then significantly reduced to a RMS value of 180 kHz over a 2 min period when the loop is closed, with the lock-in time constant set at $\tau = 30$ ms. Deliberate, temperature induced wavelength perturbations of the pump laser, at 28 seconds and 55 seconds, were nullified by the control loop, thus keeping the laser emission wavelength constant at the gas line centre. Comparable experimental results using saturated acetylene transitions in gas cells include those by Balling et. al., where the optical frequency of a modulated DFB is stabilized to a value of ≈ 10 kHz using third-harmonic techniques [24,25], as well as Nakagawa et. al. who managed to stabilize a high-power DFB narrow linewidth laser diode with an absolute frequency accuracy of ≈ 20 kHz [26].

In order to further demonstrate the stabilisation capabilities of this technique, the laser diode temperature was changed in a controlled manner while the feedback loop was implemented. Successful results are shown in Fig. 3(b), with the error signal amplitude increasing to compensate for a total temperature change of the DFB laser of $\Delta T = 0.05^\circ\text{C}$. This temperature change is equivalent to an open-loop frequency drift of the laser diode optical output of more than 650 MHz, significantly bigger than the measured absorption line Doppler linewidth of $\Delta\nu_D = 470$ MHz. The frequency stability attained for both constant and variable laser temperatures could be improved by reducing the linewidth of the saturation dip by some of the methods described elsewhere in this paper, as well as minimising the transmission/stray reflections effects that somewhat distort the shape of the saturated 1f feature.

Conclusions

A novel technique for modulation-free laser frequency stabilisation based on gas saturation effects and WM techniques in HC-PBFs was demonstrated. In the first part the main saturation parameters of acetylene absorbing transitions using WM techniques have been characterized, with a saturation level of about 2% and 50 MHz linewidth for fibre input powers of approximately 40 mW. In the second part the modulation-free laser stabilisation technique was proposed and demonstrated for a high-power DFB laser diode, stabilizing the emission frequency to a RMS value of 180 kHz for both constant laser temperature and over a range of 0.05°C . The significant stabilisation attained could be further improved by optimizing parameters such as the gas pressure or fibre geometry, maintaining the simple set-up and achieving stabilisation figures similar to other more complex schemes. This novel technique can be extended to different types of saturation media and lasers providing a very useful way of stabilizing the operating wavelength in saturation spectroscopy experiments, thus improving both the accuracy and potential applications.

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