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RESEARCH ARTICLE

Calibration of grating based optical spectrum analyzers

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Abstract In this paper, three methods are used to calibrate a grating-based Optical Spectrum Analyzer (OSA). The first method is used to calibrate OSA over the full spectral range by using a set of well characterized laser sources. These lasers, whose wavelengths cover OSA range, are well characterized using a highly accurate wavemeter. The Accuracy and stability for some lasers are found sufficient to calibrate OSA without the need to have an online measurement with a wavemeter. The second method uses the advantage of phase matching in non-linear crystals to generate frequency doubled light with exactly half the wavelength to measure OSA wavelength scale accuracy, resolution and linearity. In the third method, a Hydrogen Cyanide ($\text{H}^{13}\text{C}^{14}\text{N}$) gas cell - (HCN) is used as wavelength reference to calibrate OSA in the wavelength range 1533–1557 nm.

Keywords Optical spectrum analyzer · Hydrogen cyanide wavelength reference

Introduction

Fiber optical communication is still rapidly developing with the constant introduction of newer technologies to increase the

communications bandwidth. The most widely used new technology is the dense wavelength division multiplexing (DWDM) [1]. DWDM requires tight specification and therefore measurement of wavelength accuracy and stability of communication lasers. This specification is required because of precise channel allocation and detection requirements. Up to 80 different laser wavelengths (optical channels within wavelength range of 1520–1570 nm) can be used in DWDM. This increases the communication bandwidth from about 1 Gb/s to about 100 Gb/s, which allows high speed data transmission.

Optical Spectrum Analyzers (OSA) are widely used to measure the absolute wavelength and spectral purity of laser sources which are used in DWDM. Calibration of OSA is necessary to ensure accurate measurement of laser characteristics. Characterization of laser sources is not only important for DWDM systems, but also for other telecommunication applications. For example, laser spectral purity determines the chromatic dispersion in an optical communication system and hence the bandwidth. Therefore, it is important to calibrate OSAs over the full wavelength scale. Although there is already a standard method describing the main principle of OSA calibration [2], a novel calibration technique is introduced in this paper based on the exact frequency ratio between the fundamental and the second harmonic of frequency doubled laser to calibrate the wavelength scale of an OSA. In addition, the paper gives a comparison between different techniques and practical considerations during calibration.

In this work, three methods will be used to calibrate the main key parameters affecting the measurement results. The key parameters of interest are: 1- Center wavelength accuracy 2-Linearity of the wavelength scale and 3- Resolution

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Bandwidth. The first method uses a set of laser sources which is located at different wavelengths along OSA range. These lasers are well characterized using accurate wavemeter and the results are stated. This wavemeter was previously calibrated as described in reference [3]. In the second method, the fundamental as well as the frequency doubled light generated from a nonlinear crystal at 1556 nm and 778 nm respectively is used to calibrate OSA wavelength scale accuracy, resolution and linearity. In the third method, a Hydrogen Cyanide ($\text{H}^{13}\text{C}^{14}\text{N}$) gas cell - (HCN) is used as wavelength standard to calibrate OSA in the wavelength range 1533–1557 nm.

Grating-based optical spectrum analyzers

The main block of a grating-based OSA is a monochromator [4]. Figure 1 shows a basic configuration of a monochromator. The monochromator has a planar diffraction grating and two concave mirrors. The incident light from the optical fiber is made parallel by a collimating mirror, and diffracted at the diffraction grating. Then this light reflects on a focusing mirror and dispersively forms a spectrum on the slit plane. Only the light with the intended wavelength will be focused at the slit and can pass it through.

The resolution bandwidth (RBW) of the monochromator is given by the following equation.

$$RBW = \frac{\varepsilon d \cos(\theta)}{m f}$$

Where, (d) is the grating pitch, (m) is the diffraction order, and (θ) is the angle between the outgoing beam and the normal line to the reflection plane. It is clear from the equation that better resolution could be obtained for longer focal length (f) of the focusing mirror or narrower width (ε) of the slit.

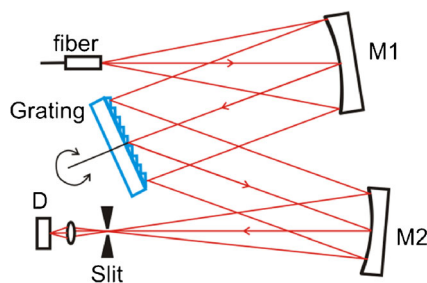


Fig. 1 Monochromator configuration, M1: collimating mirror, M2 focusing mirror, D: photodetector

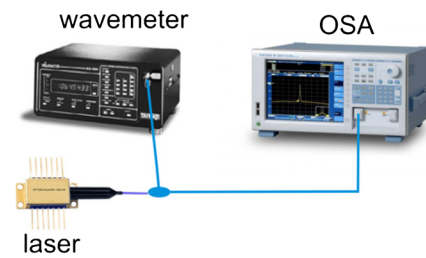


Fig. 2 Optical spectrum analyzer (OSA) calibration setup using accurate wavemeter

Experiment

System configuration

In this paper three methods will be used to calibrate the wavelength scale of an OSA. In the first and the second methods, lasers wavelength are measured simultaneously with an accurate wavemeter and the OSA under calibration, as shown in Fig. 2. The wavemeter is Burleigh 1500 and the OSA is Yokogawa AQ6370C. The lasers are from different suppliers such as Thorlabs and EM4. The frequency doubling crystal is (HCPhotonics, SC1302180031, length 40 mm).

In the third method, a reference Hydrogen Cyanide ($\text{H}^{13}\text{C}^{14}\text{N}$) gas cell is used, see Fig. 3. The cell is purchased from Traid technology with specified gas pressure at 23 C of 100 Torr \pm 5 %, HCN purity of 98 %, temperature dependence < 0.0001 nm/ $^{\circ}\text{C}$ and wavelength accuracy of ± 0.0003 nm (1 sigma). $\text{H}^{13}\text{C}^{14}\text{N}$ gas contains absorption lines in the wavelength range 1528–1563 nm. In order to probe these absorption lines an Erbium-doped fiber amplifier (EDFA) (Pritel SA-30) is used as a broadband source. The EDFA emits a broad spectrum over the wavelength range (1533–1557 nm) with power > -30 dBm/nm.

Results and discussion

First calibration method employing laser sources

The lasers that are used for OSA calibration must have stability much better than OSA resolution during the

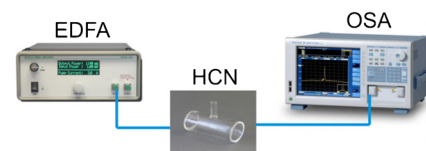


Fig. 3 Optical spectrum analyzer (OSA) calibration setup using $\text{H}^{13}\text{C}^{14}\text{N}$ reference gas cell

Table 1 Lasers characterization with wavemeter

N	Measured wavelength (nm)	Accuracy (nm)	Stability (ADEV<100 s)	Laser type	Condition	
					Laser temp. (°C)	Injection current (mA)
1	611.9705	$< \pm 0.0002$	$< 8 \times 10^{-7}$	He-Ne	—	—
2	632.9914	$< \pm 0.0002$	$< 6 \times 10^{-7}$	He-Ne	—	—
3	652.7707	± 0.050	$< 2 \times 10^{-6}$	FP	25.43	38.8
4	663.1537	± 0.070	$< 2 \times 10^{-6}$	External Cavity Tunable Laser (ECDL)	20.9	(PZT=0 V)
5	668.1632	± 0.070	$< 2 \times 10^{-6}$			
6	673.1359	± 0.070	$< 2 \times 10^{-6}$			
7	678.1191	± 0.070	$< 2 \times 10^{-6}$			
8	779.0288	$< \pm 0.0002$	$< 4 \times 10^{-7}$	DFB	22.43	125
9	860.2332	± 0.0014	$< 3 \times 10^{-7}$	FP	22.87	41.8
10	964.6923	± 0.003	$< 2 \times 10^{-6}$	FP	22.7	44.1
11	1312.5527	± 0.006	$< 5 \times 10^{-7}$	FP	22.49	7
12	1556.0308	± 0.004	$< 8 \times 10^{-8}$	DFB	33.100	80

FP Fabry-Perot Diode Laser, DFB Distributed Feedback Diode Laser

measurement. In addition, they must have much better accuracy than OSA, if they are used without a wavemeter. Therefore, the wavemeter is initially used to analyze the stability and the accuracy of such twelve laser lines that cover the wavelength range 612–1556 nm. The following table (Table 1) summarizes the results.

The second column (measured wavelength) describes the average wavelength of several measurements done by switching off and on the lasers and allows them to be thermally stabilized before performing measurements. The third column (Accuracy) describes the maximum change in lasers wavelength during these measurements. The fourth column (stability) describes stability of the laser during a single measurement (without switching the laser off and on).

It could be concluded from the above results that lasers 1, 2, 8, 9, 11, and 12 can be used to calibrate an OSA without the need to have a simultaneous measurement with wavemeter. The reason behind this is their wavelength accuracy appeared to be much better than OSA accuracy. Since the lasers stability during calibration should be better than OSA accuracy, stability measurements has been performed on each laser. As an example, a measurement made with a wavemeter for 600 s for a 779 nm DFB laser. Time data and Allan deviation (ADEV) is shown in Fig. 4. All lasers are found to satisfy this condition and they all can be used for calibration. Many other pre-characterized and highly stabilized lasers could be used without the need for wavemeter [5, 6].

Fig. 4 **a** Wavelength fluctuations for a DFB laser (at 779 nm) and **b** the corresponding ADEV

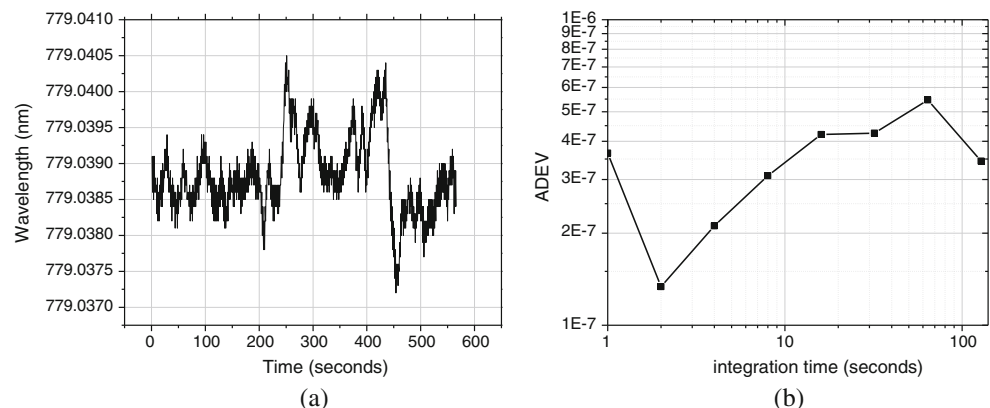


Table 2 OSA calibration with different laser sources

Wavemeter (λ_1)	OSA (λ_2)	d λ
611.9709	611.987	-0.0161
632.9915	633.026	-0.0345
652.7665	652.779	-0.0125
663.1443	663.164	-0.0197
668.1161	668.132	-0.0159
673.0702	673.09	-0.0198
678.0229	678.039	-0.0161
860.2345	860.235	-0.0005
964.698	964.694	0.0040
969.3037	969.298	0.0057
1312.5765	1312.589	-0.0125
1556.0306	1556.03	0.0006

Afterwards, the above mentioned lasers are used to calibrate the OSA using the system described in Fig. 2. The results are shown in Table 2:

Almost all of the measurements are falling within the 20 pm OSA resolution. However, the relatively larger error for 633 nm wavelength more than that of the 1556 nm is attributed to the self-calibration process inside the OSA which uses a gas cell with reference absorption lines near 1550 nm. Moreover, there is no apparent linear relation between the error and the wavelength, see Fig. 5.

The measurement accuracy of the OSA is less than 1 pm for the wavelengths near 1556 nm. In order to confirm this result and to measure the resolution of OSA near 1556 nm, additional superior accuracy fiber laser at 1556 nm is used

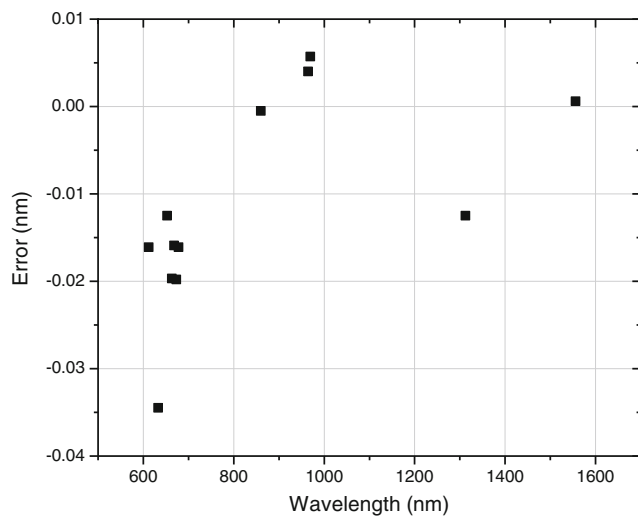


Fig. 5 Errors of the OSA under calibration against lasers wavelength

± 1 pm. The wavelength of the fiber laser is changed by small steps of 10 pm over a range of 1 nm and 1 pm over range of 10 pm. OSA shows accuracy within ± 2 pm and resolution of 1 pm as shown in Fig. 6:

Second calibration method employing frequency doubling

It is also possible to test the accuracy, resolution and linearity of OSA by using frequency doubling in nonlinear crystal. The fiber laser, which has a narrow linewidth of 1 kHz and wavelength of 1556 nm is frequency doubled using a waveguide PPLN crystal. The generated second harmonic spectral line has exactly half of the fundamental wavelength of the fiber laser, that's to say 778 nm but double the linewidth. The accuracy is measured using the fiber laser installed in the system shown in Fig. 2. The linearity is tested by measuring the wavelength of the second harmonic at 778 nm using also the system in Fig. 2. The resolution is tested by measuring the linewidth of both the fundamental and the second harmonic wavelengths of the fiber laser. The resolution of OSA is adjusted at the lowest possible value of 0.02 nm and a measurement is taken. A Gaussian fit is applied to the measured data, see Fig. 7.

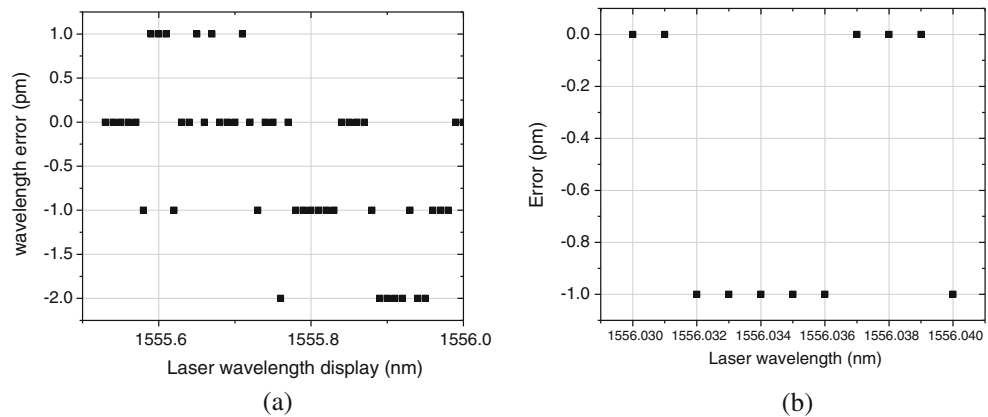
The OSA accuracy is tested as discussed in the previous section. The OSA linearity is tested, by getting use of the fact that the 1556 nm is exactly double of the 778 nm. The measured wavelength by OSA at 778 nm should be exactly the half of the measured wavelength at 1556 nm; however, a difference of 16.5 pm is found between both measurements ($\Delta\lambda = \lambda_{\text{SHG}} - \lambda_{\text{F}/2} = 778.082 - 778.0985 \text{ nm} = 16.5 \text{ pm}$). This difference lies within the resolution of the OSA, therefore, can be neglected. The line-width of the fiber laser measured using OSA is 14 pm, which indicates OSA resolution near 1556 nm. The measured line-width of the second harmonic is increased for the second harmonic laser (778 nm) to be 41 pm. The linewidth is expected to be the double of the 14 pm (28 pm); however the increase in the detected linewidth from 28 to 41 pm is attributed to the wavelength dependence of the OSA on the resolution.

In order to confirm the resolution dependence on wavelength, additional linewidth measurement is done with very narrow linewidth red He-Ne laser (kHz range) at 633 nm. A Gaussian fit on the measured curve shows a linewidth of 55 pm, see Fig. 8.

Third calibration method employing hydrogen cyanide ($\text{H}^{13}\text{C}^{14}\text{N}$) gas cell

Hydrogen Cyanide ($\text{H}^{13}\text{C}^{14}\text{N}$) gas cells provide an accurate wavelength reference for calibration of OSAs in the c-band.

Fig. 6 Errors of OSA measured with fiber laser **a** every 10 pm steps **b** every 1 pm step



The center wavelengths of 54 lines of the $2\nu_3$ rotational-vibrational band of hydrogen cyanide $\text{H}^{13}\text{C}^{14}\text{N}$ are also certified with uncertainties ranging from 0.04 to 0.24 pm. Therefore it is commonly used as a first choice when calibrating OSAs especially due the simple optical setup needed and it always carries a relatively low price tag. By using the setup in Fig. 3, additional OSA calibration has been made with reference to a $\text{H}^{13}\text{C}^{14}\text{N}$ gas cell. The absorption peaks of this gas cell when measured with OSA are shown in Fig. 9.

The absorption lines in Fig. 9 are called the R, P branches with labels starting from R0 and P1 at the center and could be extended to R26, P27 [7].

However due to the bandwidth limit of the EDFA, the measurement is made over a smaller range. The absorption line centers are then tabulated in Table 3. The reference line centers at zero pressure is deduced from reference n and written in the same table. For pressure of 100 Torr (13.3kPa), a correction is applied for the pressure shift as indicated in the same reference. This correction is less than 0.3 pm, and hence not significant to OSA calibration.

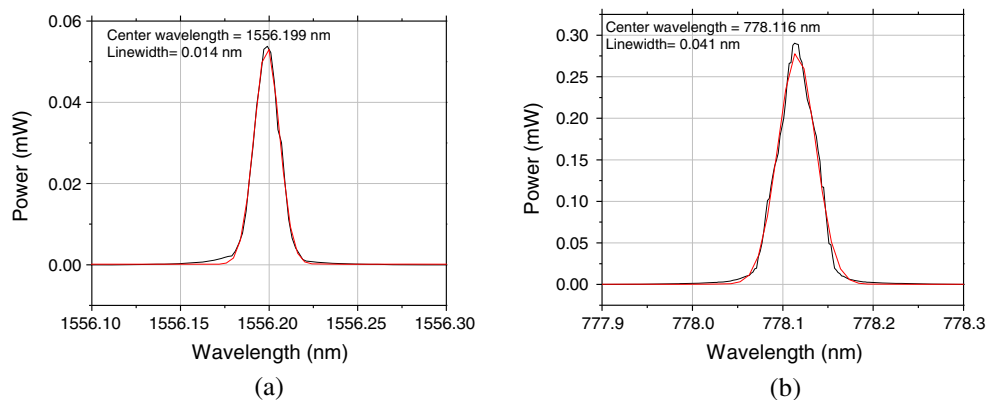
As demonstrated in Table 3, the maximum deviation of the measured HCN lines by OSA never exceeded \pm

6 pm. Therefore, the accuracy and the linearity of the OSA measurement at the wavelength range from 1533 to 1555 nm is reported to be ± 6 pm. This result lies within the resolution of the OSA (20 pm) and in good match with the previous accuracy results using different lasers at section A, which was around 1 pm at 1556 nm.

Conclusion

In this paper, three methods are used to calibrate a grating-based Optical Spectrum Analyzer (OSA). A set of 9 lasers (12 wavelengths) is well characterized in terms of stability and accuracy to be applied for the calibration of OSA. The Accuracy and stability for some lasers are found sufficient to calibrate OSA without the need to have an online measurement with a wavemeter. The accuracy of the wavelength scale of OSA is found to be wavelength dependent, since the error is 35 pm at 632 nm and less than 1 pm at 1550 nm. However, no linear relation between the

Fig. 7 Measurement of OSA resolution and linearity using a narrow linewidth fiber laser **(a)** and the second harmonic **(b)**



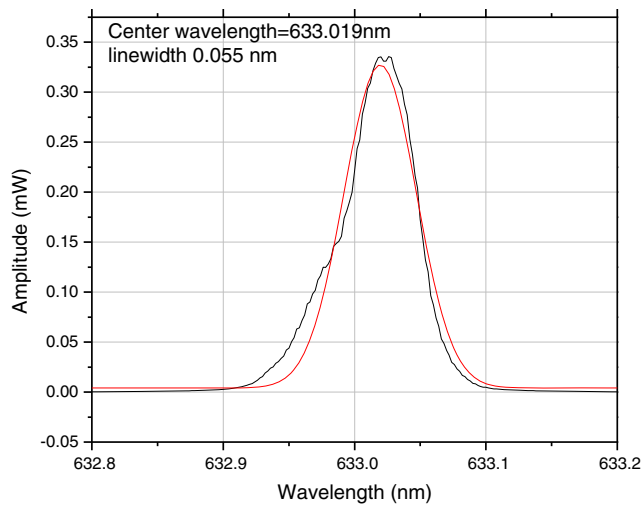


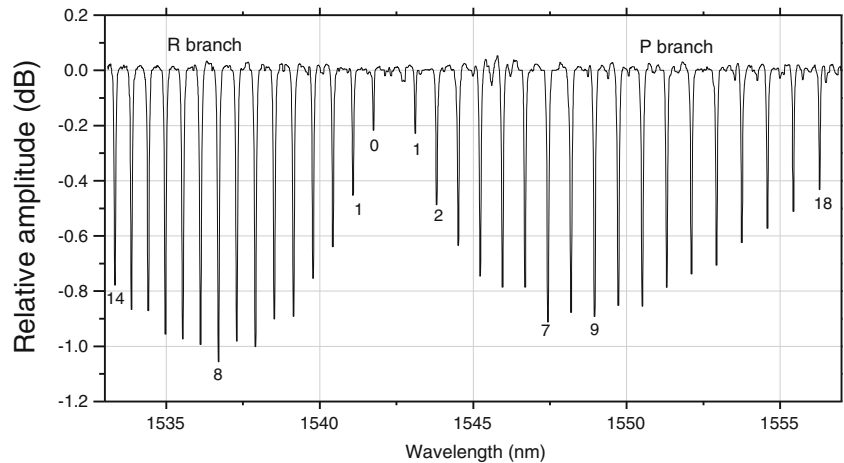
Fig. 8 Linewidth measurement by He-Ne 633 nm laser

wavelength and the error has been observed. This behavior near 1550 nm is confirmed by very stable fiber laser which is fine tuned near 1550 nm and measured by wavemeter and OSA simultaneously. The error is found to be within ± 2 pm. A fundamental laser at 1556 nm and its second harmonic is used to check the wavelength accuracy, resolution and linearity. A deviation between both fundamental and second harmonic component of 16 pm is found. The resolution can be deduced from the measured linewidth of both components. It is found to be 14 pm at 1550 nm and 41 pm at 778 nm. Finally, a Hydrogen Cyanide ($\text{H}^{13}\text{C}^{14}\text{N}$) gas cell - (HCN) is used as wavelength reference to calibrate OSA in the wavelength range 1533–1557 nm. A maximum deviation of the measured HCN lines by OSA never exceeded ± 6 pm. We conclude from the above measurements that the accuracy near 1550 nm will never exceed ± 6 and the resolution is always less than 15 pm. For other wavelengths the accuracy can be better than 35 pm and the resolution is around 51 pm.

Table 3 OSA calibration with HCN gas cell

Label	OSA (nm)	HCN (nm)	d λ (pm)
R branch			
R 14	1533.330	1533.3292092	0.8
R13	1533.870	1533.8671492	2.9
R12	1534.415	1534.4149297	0.1
R11	1534.975	1534.9723592	2.6
R10	1535.540	1535.5397107	0.3
R9	1536.115	1536.1167967	−1.8
R8	1536.700	1536.7036631	−3.7
R7	1537.300	1537.3003731	−0.4
R6	1537.905	1537.9067229	−1.7
R5	1538.520	1538.5233077	−3.3
R4	1539.145	1539.1494296	−4.4
R3	1539.785	1539.7855917	−0.6
R2	1540.430	1540.4314306	−1.4
R1	1541.085	1541.0873277	−2.3
R0	1541.750	1541.7530147	−3.0
P branch			
P1	1543.115	1543.1140707	0.9
P2	1543.810	1543.8093809	0.6
P3	1544.515	1544.5146909	0.3
P4	1545.230	1545.2300117	−0.0
P5	1545.955	1545.9551947	−0.2
P6	1546.690	1546.6902479	−0.2
P7	1547.435	1547.4353419	−0.3
P8	1548.190	1548.1904069	−0.4
P9	1548.955	1548.9555347	−0.5
P10	1549.730	1549.7305737	−0.6
P11	1550.515	1550.5156157	−0.6
P12	1551.310	1551.3105653	−0.6
P13	1552.115	1552.1156453	−0.6
P15	1552.930	1552.9308657	−0.9
P16	1553.750	1553.7558794	−5.9
P17	1554.590	1554.5912284	−1.2
P18	1555.435	1555.4365257	−1.5

Fig. 9 Absorption lines of $\text{H}^{13}\text{C}^{14}\text{N}$ gas cell measured with OSA



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