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# TECHNIQUE OF BROADBAND MEASUREMENTS OF FREQUENCY CONVERSION EFFICIENCY FOR EACH HARMONIQUE IN FREQUENCY MULTIPLIERS UP TO TERAHERTZ RANGE

**A. F. Krupnov, M. Yu. Tretyakov, G. Yu. Golubyatnikov, A. M. Schitov, S. A. Volokhov, and V. N. Markov**

*Institute of Applied Physics of Russian Academy of Sciences*
*46 Uljanova Street*
*Nizhny Novgorod 603600, Russia*

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## Abstract

The paper describes technique of quantitative analysis of a millimeter- and submillimeter-wave range multipliers performance in particular the measurement of the frequency conversion efficiency. The output power on each harmonic produced by the multiplier can be measured separately without any changes in the setup even in the case of simultaneous emission of all harmonics including the fundamental in a frequency range up to 1 THz and well above.

The measuring technique primarily developed for high resolution microwave spectroscopy is based on absorption of radiation in spectral lines of rarefied sample gas and photo - acoustic method of the absorption detection. Sensitivity independence of the detection method on frequency and well known spectral parameters of the lines provide the technique with broadbandness, high spectral resolution and power measurement reliability. Principal limits of measurable radiation power may vary from nanoWatts up to hundreds of Watts. The technique permits real time operation convenient, e.g., for multiplier tuning.

Practical examples include measurements of harmonic generation efficiency of multipliers of 78-118 GHz fundamental frequency range, and power measurement up to 6-th harmonic of 230 GHz fundamental radiation of phase locked Backward Wave Oscillator (BWO).

Keywords: Multipliers, harmonics, conversion losses, spectral lines, millimeter- and submillimeter waves.

# 1. Introduction

Use of frequency multipliers as alternative radiation sources in millimeter- and submillimeter-wave range for microwave spectroscopy, radioastronomy, microwave measurements etc is widely known.

The most important characteristic of multipliers is conversion loss or frequency conversion efficiency of the power of fundamental radiation to the power of harmonic(s). At the same time measurements of this characteristics by common microwave methods are connected with some difficulties, mostly related with technical problems to keep known a sensitivity and to vary properly a spectral resolution of the measuring setup while measured frequencies of radiation differs several times and its power varies by many orders of magnitude. The difficulties of the characteristic measurement considerably increase at highest microwave frequency range exceeding now 1 THz.

This paper presents the fully PC controlled technique which allows to perform quite easily the quantitative spectrum analysis of microwave radiation source in discrete but very large number of frequency points, covering whole millimeter- and submillimeter-wave range.

# 2. General considerations

The basic idea of the technique can be shortly described as follows. A modulated (AM/FM) radiation of coherent microwave source is directed into a vacuum cell of photo-acoustic detector filled by low pressure gas sample with well known spectral lines. An acoustic signal (pressure variations) arising via gas heating up while radiation frequency has coincided to the frequency of molecular absorption line is detected by sensitive microphone. Detailed description of acoustical detection of the signals from microwave lines in rarefied gas up to THz range is given in [1].

The acoustic signal can be defined as follows:

$$A = CP_{abs} = CP_0 \cdot (1 - e^{-\gamma l}) \qquad (1)$$

where $A$ - the signal amplitude, $C$ - apparatus coefficient, $P_0$ and $P_{abs}$ - incident and absorbed by gas radiation power respectively, $\gamma$ - absorption coefficient of a spectral line, and $l$ - absorption path equal to a length of the gas cell.

Absorption coefficients of known spectral lines in millimeter- and submillimeter-wave range vary in a wide limits from more than $10^{-1}$ down to $10^{-9}$ (and even less) $cm^{-1}$, what means that in most cases with $l \sim 10$ cm the optical depth $\gamma l << 1$, so simplified relation could be used:

$$A \cong CP_0 \cdot \gamma l \,. \qquad (2)$$

Thus the acoustic signal from molecular spectral line is proportional to the microwave power passing through the cell, and therefore it can be used as radiation power indicator. Linear dependence upon the line absorption coefficient may be used for adjusting of input power level to convenient measurement interval by choosing of spectral line with appropriate radiation absorption coefficient. The spectral lines serves therefore as frequency selective filter/element analyzing spectral characteristics of the radiation as well as calibrated power indicators, responding in proportion to the radiation power.

A sensitivity limit of weak line detection by photo—acoustic receiver for room temperature, 10 cm absorption path length and integration time 1 sec is:

$$\gamma_{min}\,(cm\text{-}1) \cong 4 \cdot 10^{-11}/P_0\,,$$

where $P^0$ is radiation power in Watts [1]. This means that using spectral line with absorption coefficient $10^{-2}$ $cm^{-1}$ as power indicator such detector has NEP of about $4 \cdot 10^{-9}$ $W \cdot Hz^{-1/2}$.

The ultimate input power is limited by spectral line saturation effect and can be rather high. Values of saturation power can be estimated from:

$$P_{sat} \sim \frac{3h^2(\Delta\nu)^2 cS}{8\pi\left|\mu_{ij}\right|^2} \qquad (3)$$

where $h$ - Planck's constant, $\Delta\nu$ - line's HWHM, $c$ - speed of light, $S$ - cell's cross - section, and $\mu_{ij}$ - matrix element of dipole moment of the transition $i \leftarrow j$ of the molecule [2].

It should be noted that $\mu_{ij}$ varies from the value of permanent electric dipole moment of the molecule $\mu$ (typically of the order of 0.1÷1 Debye [1]) to the very small (but known) quantities, listed for every line. For real practical case $\Delta\nu = 20$ MHz, $S = 2$ $cm^2$ and assuming $\mu_{ij}$ is about of $\mu \sim 1$ Debye, one can obtain $P_{sat} \sim 12$ W, but this value can be easy increased in orders of magnitude by choosing a line with smaller matrix element of dipole moment, or by using higher pressure for increasing of the linewidth. The saturation power tends to increase as the square of both values, for example, for gas pressure in 3 times higher in the same practical case the saturation power increases up to 110 W [2].

In the microwave range where collisional broadening prevail in the range of pressures higher than 0.1 Torr the spectral line peak absorption coefficient $\gamma_0$ is pressure independent [4], and can be conveniently used as characteristic of the line in measurements.

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[1] 1 Debye = $10^{-18}$ esu.

[2] In one experiment with the line having small matrix element of dipole moment we used radiation power as large as 1 kW [3]. That experiment was not connected with frequency multiplication.

Spectral resolution of this technique is determined by molecular linewidth. Typical pressure broadening of molecular spectral lines is about 10 - 20 MHz Torr , i.e., at 1 Torr spectral lines have 10 - 20 MHz HWHM. Line on the *n*-th harmonic, evidently has observed width *n* times lesser than line on the fundamental frequency due to faster frequency change on the harmonic. This may serve as criterion of the line identification in addition to the line central frequency.

The sensitivity of photo-acoustic receivers are principally independent from radiation frequency. Only absorbed power produces a signal. From this very important property of the acoustic detector used in the described technique is coming: signal on one absorption line corresponding to the one of the harmonics is received without any effects from much larger powers simultaneously passing through the cell at other frequencies outside of the absorption lines.

Time constant of gas cell which is determined by time of temperature exchange between the absorbing gas and the gas cell walls is much faster than time constant of metal film which serves as power absorber in some modern power meters (e.g. the Thomas Keating TeraHertz Absolute Power Meter System [3]). Thus faster modulation rate (up to 1 kHz for our device) to reduce effect of $1/f$ noises is permitted.

The frequency multiplier conversion efficiency of input power $P_1$ into power of the *n*-th harmonic $P_n$ can be obtained from Eq. (1). For small optical depth $\gamma l << 1$) the expression deduced from Eq.(2) is:

$$\frac{P_n}{P_1} = \frac{A_n / \gamma_n}{A_1 / \gamma_1} \qquad (4)$$

A choice of the sample gas depends on speciality of analyzed multiplier as well as on particular demands of the analysis and may be very wide. But for majority of practical cases $SO_2$ gas was found to be very convenient. Lines of $SO_2$ practically uniformly cover the whole microwave range. In our list there are over 10 000 lines covering 0.5-2000 GHz range i.e. about 10 lines/GHz. Frequencies and absorption coefficients of rotational spectral lines can be easily and reliably calculated, most of them are presented in line catalog databases JPL, GEISA, HITRAN etc [4].

Thus measurement of the frequency conversion efficiency consists of choosing of pair of suitable lines for fundamental and harmonic frequencies, tuning of the radiation source at these frequencies, measuring the line response amplitudes, and then calculating ratio from Eq. (4). Then, if necessary, repeat this procedure for the next frequencies.

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[3] See e.g., http://qmciworks.ph.qmw.ac.uk/tki/pmeter.htm

[4] Our recent publication on $SO_2$ spectrum up to 1 THz appeared in [5]; authors may provide full list of lines in electronic form by request.

# 3. Apparatus

Computer controlled frequency synthesizer of type of [6] with output power 7÷15 mW at 78÷118 GHz range and BWO of type of [7] with output power about 150 mW near 230 GHz stabilized by phase-lock loop (PLL) [8] against aforementioned synthesizer have been used as primary radiation sources.

The synthesizer's radiation was amplitude modulated by *p-i-n* diode, BWO's one - by mechanical chopper. In both cases modulation frequency rate was 170 Hz.

A small angle horns were used for source/multiplier output matching to the gas cell aperture.

The acoustic gas cell is a single-pass tube ~10 cm long, ~1.5 cm in diameter with Teflon windows. Receiver of the acoustical signal is capacitance microphone in the side arm of the cell electrically included in a high frequency (5 MHz) bridge circuit. A few micrometers thickness Mylar film, coated by silver, ~5 cm in diameter, is used as microphone membrane being able to work with high enough sensitivity in rarefied gases. Typical working gas pressure in the cell is ~1 Torr. Signal from the microphone was amplified, digitized and demodulated by digital synchronous detector (DSD). Output of the DSD represented the useful signal and was stored and analyzed by computer.

Spectral lines were recorded scanning frequency of the millimeter-wave synthesizer. Typical total time of one line record was about 200 seconds: up and down frequency scan, 100 frequency points per record, integration time 1 sec. Amplitude of line was obtained from fitting of the recorded line shape to Lorentzial profile.

# 4. Experiment

First experiment demonstrates obtaining of output radiation characteristics of broad band multipliers in the range up to 470 GHz for several harmonics in a full continuous frequency range of the fundamental frequency source – frequency synthesizer of 78-118 GHz. The multipliers (doubler and tripler) used in the experiment were designed for the synthesizer frequency range extension [9]. The frequency conversion efficiency for each harmonic were measured in about 10 frequency points covering all the range of the fundamental. This gives a full enough information because of quite smooth character of the dependencies.

The measurement procedure was as follows: First of all output power characteristic of the synthesizer was obtained. Eleven spectral lines of sulfur dioxide ($SO_2$) which was used as a sample gas in this experiment were recorded in the synthesizer frequency range. In accordance to Eq. (2) the power of the

synthesizer at frequency of every line can be obtained from the observed line amplitude and the line absorption coefficient as:

$$P \cong \frac{A}{\gamma l C} \tag{5}$$

Just for comparison and for the proposed method ability proof we've measured the power of the synthesizer by commercial power meter of type of M3-75 (firm "Elmica", Vilnus, Lithuania). The result of such two power measurements is given in Fig.1.

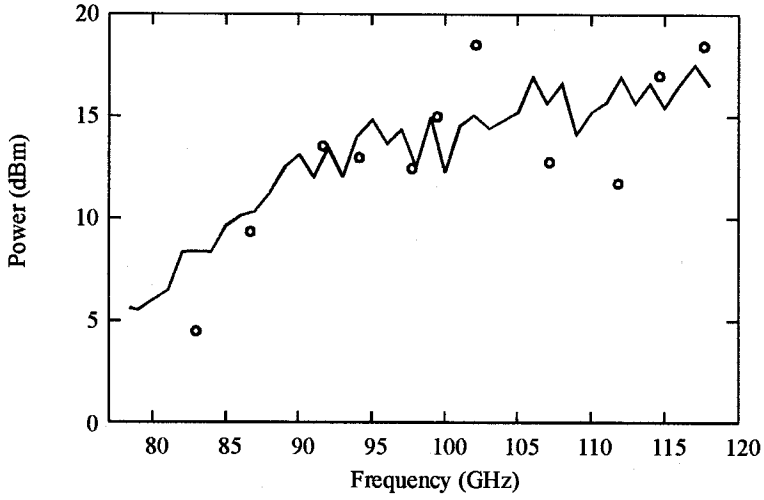


Fig.1. Output power of 78-118 GHz synthesizer measured by power meter (solid line) and using SO2 spectral lines (circles). The constant value of apparatus coefficient C was chosen so obtained from line amplitudes power match in average the power meter data.

Standard deviation of the differences between data obtained by power meter and by the described method was found about 0.7 dBm (or 6% from mean measured power). The greater part of this discrepancy is conditioned by interference in microwave tract (reflection on cell windows, horns etc) and it could be of necessity eliminated.

After the source power calibration one of the multipliers was placed between the synthesizer and gas cell and spectral lines on harmonics were recorded. In every frequency point the frequency conversion efficiency was calculated using equation (4). Value of $A_1/\gamma_1$ at corresponding frequency point was taken from the source power characteristics obtained before.

Results of the measurements are presented in Fig.2. In addition to the second and third harmonics which were objects of primary interest, the fourth harmonic produced by the doubler was observed and measured.

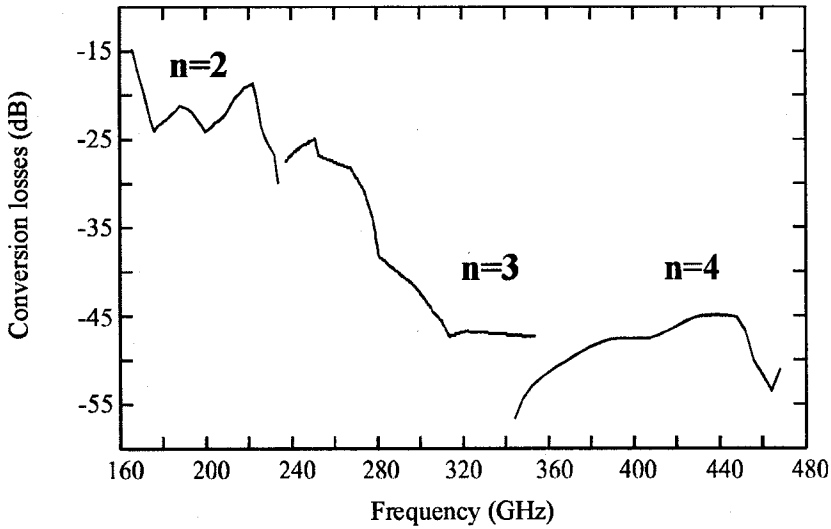


Fig.2. Characteristics of frequency multipliers at 2-nd, 3-rd and 4-th harmonics of fundamental 78-118 GHz primary radiation source.

Characteristics of the $SO_2$ spectral lines used for measurements and calculations are listed in Table 1.

The second experiment illustrates study of the frequency conversion efficiency in the continuous sequence of harmonics up to highest observable with our acoustic detector produced in one frequency point of the fundamental frequency source – the locked-in BWO at 230 GHz. The 2-nd, 3-rd, 4-th, 5-th and 6-th harmonics were observed and measured. The multiplier used in this experiment is described in [10].

For convenience of the experiment sample of carbon monoxide *CO* having almost equidistant rotational spectrum [11] was chosen.

| $n$ | $\nu_0$ (MHz) | $\gamma_0$(cm$^{-1}$) | $J'k'_ak'_c$ | $J''k''_ak''_c$ | Isot. | $\nu_1\nu_2\nu_3$ |
|---|---|---|---|---|---|---|
| 1 | 82951.949 | $1.28\cdot10^{-4}$ | $14_{3\,11}$ | $13_{4\,10}$ | 32 | 000 |
| 1 | 86639.097 | $1.03\cdot10^{-4}$ | $9_{2\,8}$ | $8_{3\,5}$ | 32 | 000 |
| 1 | 91550.442 | $1.57\cdot10^{-4}$ | $19_{4\,16}$ | $18_{5\,13}$ | 32 | 000 |
| 1 | 94064.689 | $1.40\cdot10^{-4}$ | $24_{5\,19}$ | $23_{6\,18}$ | 32 | 000 |
| 1 | 97702.348 | $1.12\cdot10^{-4}$ | $8_{2\,6}$ | $7_{3\,5}$ | 32 | 000 |
| 1 | 99392.508 | $1.41\cdot10^{-4}$ | $28_{5\,23}$ | $29_{4\,26}$ | 32 | 000 |
| 1 | 102031.892 | $1.31\cdot10^{-5}$ | $2_{0\,2}$ | $3_{1\,3}$ | 34 | 000 |
| 1 | 107060.211 | $1.48\cdot10^{-4}$ | $26_{4\,22}$ | $27_{3\,25}$ | 32 | 000 |
| 1 | 111755.009 | $8.72\cdot10^{-5}$ | $30_{4\,26}$ | $31_{3\,29}$ | 32 | 000 |
| 1 | 114565.365 | $1.29\cdot10^{-4}$ | $28_{4\,24}$ | $29_{3\,27}$ | 32 | 000 |
| 2 | 160342.955 | $2.88\cdot10^{-3}$ | $18_{1\,17}$ | $18_{2\,16}$ | 32 | 000 |
| 2 | 165225.458 | $1.63\cdot10^{-3}$ | $6_{0\,6}$ | $7_{1\,7}$ | 32 | 000 |
| 2 | 175275.722 | $1.33\cdot10^{-3}$ | $7_{1\,7}$ | $7_{2\,6}$ | 32 | 000 |
| 2 | 188654.971 | $1.77\cdot10^{-3}$ | $9_{1\,9}$ | $9_{2\,8}$ | 32 | 000 |
| 2 | 197142.066 | $4.23\cdot10^{-3}$ | $20_{2\,18}$ | $20_{3\,17}$ | 32 | 000 |
| 2 | 200287.417 | $4.11\cdot10^{-3}$ | $24_{2\,22}$ | $24_{3\,21}$ | 32 | 000 |
| 2 | 204246.773 | $4.33\cdot10^{-3}$ | $18_{2\,16}$ | $18_{3\,15}$ | 32 | 000 |
| 2 | 208700.344 | $1.02\cdot10^{-3}$ | $2_{1\,1}$ | $3_{2\,2}$ | 32 | 000 |
| 2 | 214689.410 | $4.39\cdot10^{-3}$ | $16_{2\,14}$ | $16_{3\,13}$ | 32 | 000 |
| 2 | 221965.226 | $4.59\cdot10^{-3}$ | $10_{0\,10}$ | $11_{1\,11}$ | 32 | 000 |
| 2 | 226300.044 | $4.36\cdot10^{-3}$ | $14_{2\,12}$ | $14_{3\,11}$ | 32 | 000 |
| 2 | 231980.516 | $3.62\cdot10^{-4}$ | $14_{2\,12}$ | $14_{3\,11}$ | 32 | 010 |
| 2 | 233724.908 | $2.48\cdot10^{-4}$ | $15_{2\,14}$ | $16_{1\,15}$ | 32 | 010 |
| 3 | 240942.780 | $2.96\cdot10^{-3}$ | $18_{0\,18}$ | $18_{1\,17}$ | 32 | 000 |
| 3 | 251199.678 | $6.83\cdot10^{-3}$ | $12_{0\,12}$ | $13_{1\,13}$ | 32 | 000 |
| 3 | 252563.873 | $8.32\cdot10^{-4}$ | $31_{5\,27}$ | $32_{4\,28}$ | 32 | 000 |
| 3 | 267537.452 | $5.10\cdot10^{-3}$ | $13_{2\,12}$ | $13_{3\,11}$ | 32 | 000 |
| 3 | 280807.258 | $6.09\cdot10^{-3}$ | $26_{3\,23}$ | $26_{4\,22}$ | 32 | 000 |
| 3 | 296535.437 | $6.91\cdot10^{-3}$ | $24_{3\,21}$ | $24_{4\,20}$ | 32 | 000 |
| 3 | 313660.846 | $1.27\cdot10^{-2}$ | $16_{0\,16}$ | $17_{1\,17}$ | 32 | 000 |
| 3 | 346652.159 | $1.60\cdot10^{-2}$ | $18_{0\,18}$ | $19_{1\,19}$ | 32 | 000 |
| 4 | 346652.159 | $1.60\cdot10^{-2}$ | $18_{0\,18}$ | $19_{1\,19}$ | 32 | 000 |
| 4 | 430193.689 | $1.50\cdot10^{-2}$ | $23_{2\,22}$ | $24_{1\,23}$ | 32 | 000 |
| 4 | 449384.129 | $2.52\cdot10^{-2}$ | $24_{0\,24}$ | $25_{1\,25}$ | 32 | 000 |
| 4 | 456352.309 | $1.40\cdot10^{-2}$ | $19_{4\,16}$ | $19_{5\,15}$ | 32 | 000 |
| 4 | 465751.138 | $2.63\cdot10^{-2}$ | $25_{1\,25}$ | $26_{0\,26}$ | 32 | 000 |
| 4 | 471894.357 | $1.79\cdot10^{-2}$ | $25_{2\,24}$ | $26_{1\,25}$ | 32 | 000 |

Table 1. Spectral lines of $SO_2$ molecule used for 78-118 GHz primary radiation source multipliers frequency conversion efficiency measurements. $n$ - harmonic number; $\nu_0$ - frequency of line center; $\gamma_0$ - absorption coefficient; $J$, $k_a$, $k_c$ - rotational quantum numbers of lower and upper state; Isot. – isotopic species of $S$ atom at the molecule; $\nu_1\nu_2\nu_3$ - vibrational state quantum numbers.

| n | $\nu_0$ (MHz) | $\gamma_0$ ($cm^{-1}$) | $J' \leftarrow J''$ | $A$ (arb.un.) | FTE (dB) |
|---|---|---|---|---|---|
| 1 | 230 538.000 | $2.7 \cdot 10^{-3}$ | $2 \leftarrow 1$ | 260 000 | 0 |
| 2 | 461 040.768 | $2.1 \cdot 10^{-2}$ | $4 \leftarrow 3$ | 9 400 | -23 |
| 3 | 691 473.076 | $6.3 \cdot 10^{-2}$ | $6 \leftarrow 5$ | 9 400 | -27 |
| 4 | 921 799.704 | $1.2 \cdot 10^{-1}$ | $8 \leftarrow 7$ | 3 500 | -33 |
| 5 | 1 151 985.444 | $1.7 \cdot 10^{-1}$ | $10 \leftarrow 9$ | 360 | -43 |
| 6 | 1 381 995.104 | $2.0 \cdot 10^{-1}$ | $12 \leftarrow 11$ | 100 | -49 |

Table 2. Spectral lines of main isotope of *CO* molecule in ground vibrational state used for the multiplier study ($\nu_0$ - line center frequency [17], $\gamma_0$ - absorption coefficient, $J'$ and $J''$ - rotational quantum numbers, $A$ - observed in the experiment line amplitude, FTE - frequency transformation efficiency, n - number of harmonic.

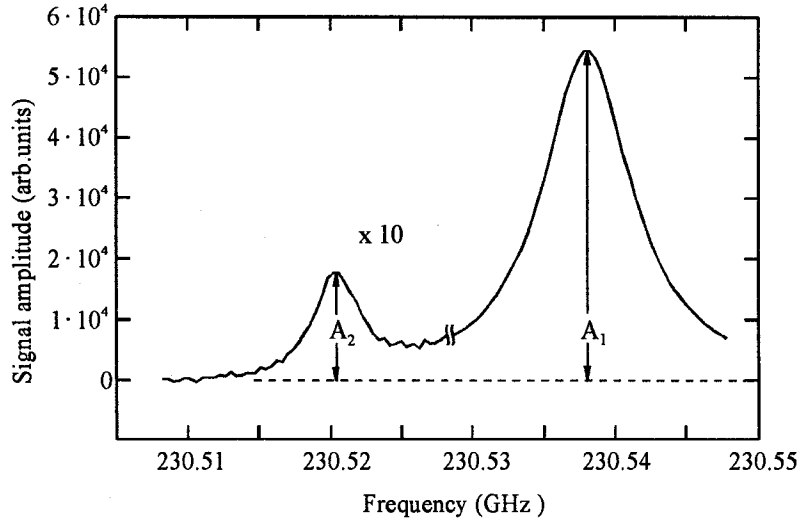


Fig. 3 An example of *CO* spectrum record. The record is made during one frequency scan with time constant about 1 second. The large line on the right corresponds to transition $J$=2←1 (see Tabl.2) at 230.538 GHz observed at fundamental frequency. The zoomed in factor of ten line on the left corresponds to transition $J$=4←3 at 461.041 GHz observed at the second harmonic. Relation between fundamental and second harmonic powers can be estimated from observed line amplitudes and the line absorption coefficients using formula (4) as $A_1\gamma_2/A_2\gamma_1 \approx 240$, which is about 24 dB.

Data of this spectrum and results of the experiment are summed in Table 2 [5]. An example of the experimental record of the part of *CO* spectrum is presented in Fig.3. The figure illustrates calculation of conversion loss into the second harmonic which is ~24 dB in this particular case.

# 5. Conclusions

As it is known, the microwave spectroscopy traditionally led the way of other microwave technique, measurements and uses in higher frequency regions [2], [4], [10]. But mostly its influence was indirect - by creating multipliers as radiation sources [2], [4], [10], improving detection technique, stabilization/measurement of the higher frequencies [6], [8], [12] etc. As a recent example the ultralow absorption measurements can be pointed out [13].

In the present work the direct use of the part of microwave spectroscopy technique has been suggested for general purpose microwave measurements in millimeter-- and submillimeter -wave range.

Examples of practical measurements of frequency multipliers performance are given up to the highest microwave frequencies of 1.4 THz range.

The well known spectral line parameters of employed gas sample in acoustic cell provides the described method by not only reliable power measurement, but a good frequency resolution over wide frequency range instead of frequency counters or spectrum analyzers. There is no need of any input frequency selective components for filtering out of neighboring harmonics of the fundamental power, or cutting them off to eliminate such effects as saturation, intermodulation, or nonlinear frequency mixing.

The technique provides wide possibilities for development, analysis, calibration and improvement of frequency multipliers widely used, in radioastronomy, spectroscopy, and microwave measurements itself. For practical purposes especially valuable is possibility of control by the described technique the multiplier tuning to the necessary power of the any harmonic(s) needed in real time regime. Considering also small size and simplicity of used measuring gauge, one can conclude that by the combination of possibilities and easiness the described technique is unique at the moment for quantitative measurements of frequency multipliers characteristics.

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[5] Since the optical depth $\gamma l$ especially for high frequency *CO* lines in our cell becomes large, the accurate expression derived from Eq. (1) was used for the frequency conversion efficiency calculation.

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