VECTOR MEASUREMENTS UP TO THE THz and BEYOND, AT SEVERAL FREQUENCIES AT THE SAME TIME

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Abstract.

The Vector Network Analyzer developed by AB MILLIMETRE since 1989 permits vector measurements in the frequency range from 8 to 1000 GHz (with a single pair of extensions) and beyond (with mutiplication chains). It is used in electrical engineering field, like in antenna measurements, and also in the domain of research in Physics, like in the magnetic resonances at high magnetic field. In this last case, working at several frequencies simultaneously saves a lot of time. In the case of antenna measurements, such possibility could also demonstrate the phase center frequency dependence without needing extremely accurate mechanical positioning.

I. Single Schottky Multipliers.

At the beginning of this new century, a large variety of research work is exploring the possibility of new sources at the THz range. See the sessions "Sources" (1). However, the most common, and traditional, way for obtaining coherent millimeter-submillimeter waves from solid-state electronics devices above 200 GHz is the use of Gunn oscillators feeding Schottky multipliers. See the sessions "Multiplication" (2). Such multipliers can be made from a single Schottky. In this case the non-linear effects generate a comb of harmonics Ma at frequencies Fmm from a Gunn A at frequency Fa:

$$Fmm = Ma \times Fa$$

where the integer Ma can take values large enough so that Fmm is above the cutoff of the multiplier's output. With appropriate mechanical tunings, one can optimize the desired harmonic. When making use of high-pass filters, undesired lower harmonics can be suppressed. When associating a widely mechanically tunable Gunn (typically Fa = 95 +/- 15 GHz), there is an overlapping of successive harmonics, so that one has the availability of a continuous frequency coverage source (we call it ESA-1-FC). Naturally, the emitted power decreases with frequency, being of the order of 1 mW ca 200-300 GHz, 0.1 mW ca 400-500 GHz, and decreasing then typically by 10.7 dB per 100 GHz (being typically 1 uW at 700 GHz, 0.6 nW at 1 THz).

II. Simultaneous scalar detection of several harmonics from the same source (multi-harmonic multiplier, or multiplication chain).

In August 2000, in order to make easier the developments and adjustments of the multi-harmonic multipliers that we needed for our "Full Coverage" submillimeter source described above (Gunn at Fa feeding a single-Schottky multiplier), we have created a new instrument called SIMUHADE (SImultaneous MUlti-Harmonic DEtector). In the SIMUHADE, a centimeter source at frequency F1 (between 8 and 18 GHz) is PLL-controlled so that its harmonic k is maintained at 10 MHz from the millimeter frequency Fa. This centimeter source is, through a flexible coax cable, the Local Oscillator LO of a sensitive tunable Harmonic Mixer HM which detects the microwaves at the multiplier output.

Visualization of the harmonics generated by the Multiplier is made easy using a 0-100 MHz scale spectrum analyzer. Each harmonic Ma appears at the frequency Ma x 10 MHz. See for instance Fig.1 the harmonics M=3-4-5 at 309-412-515 GHz, created from a Gunn at 103 GHz, and Fig.2, the harmonics M=5-6-7 at 480-576-672 GHz, from a Gunn at 96 GHz. The effects of possible adjustments on the mutiplier (bias on the Schottky, mechanical tunings) are immediately visible on the spectrum analyzer. With the smallest bandwidth compatible with a fast scan (ca 10 kHz), and with the conversion loss in the harmonic mixer HM (from 46 dB at 250 GHz, to 80 dB at 1 THz) the smallest detectable powers vary from -70 dBm at 250 GHz, to -40 dBm at 1 THz (3). Notice that the SIMUHADE can also be used when testing cascaded multiplication chains. In this case, one can observe the desired harmonic with a sensitivity better than that of a calorimeter, and also sometimes unexpected spurious signals, like M=5 after a sextupler made of a tripler cascaded by a doubler.

III. Simultaneous vector detection of two harmonics from the same source (multi-harmonic multiplier).

For the vector measurements in the range 250-1000 GHz, we associate to the Full Coverage source ESA-1-FC (a multi-harmonic multiplier) described in I., a similar single Schottky device, called ESA-2-FC (a multi-harmonic harmonic mixer), having as LO a Gunn B at the frequency Fb (Fb ≈ Fa). Both Gunns, A & B, are referenced, with PLL controls of different offsets, to the same centimeter LO inside the Vector Network Analyzer MVNA-8-350. The Gunn frequencies are maintained at a small fixed frequency difference:

$$Fa - Fb = f$$

the phase noise between them is eliminated, and the oscillator giving f can also give the phase reference to the Vector Receiver VR of the Vector Network Analyzer (4). After harmonic mixing detection, the comb of successive harmonics Ma x Fa (submillimeter waves) gives a comb Ma x f (radiofrequencies below 100 MHz) at the ESA-2-FC output. We operate the vector detection simultaneously at two frequencies when using the two channels of the Vector Receiver tuned respectively at Ma x f (on Channel 1, called "major" harmonic), and at (Ma'=Ma-1) x f (on Channel 2, called "minor" harmonic). At Gunn B, the corresponding harmonic mixing ranks are the same: Mb=Ma, and Mb'=Ma'=Ma-1. This dual-frequency capability has been intensively used in the domain of spectroscopy at high magnetic fields (5). It has also been used, for instance, in the search of resonances in whispering gallery resonators, see Fig.3.

IV. Comparison of Full-Coverage (single-Schottky), or dedicated (several Schottkys), multiplier sources.

Notice that the noise floor Pn of the MVNA-8-350 is very low, of the order of Pn=-155 dBm, due to a small equivalent detection bandwidth. If the ESA-1-FC emitted power is Pmm, and if the ESA-2-FC detector conversion loss is L, the dynamic range S/N will be given by:

$$S/N\ (dB) = Pmm\ (dBm) - L\ (dB) - Pn\ (dBm)$$

With the pair of extensions ESA-1-FC/ESA-2-FC associated to the MVNA, the observed S/N varies from ca 130 dB at 300 GHz, to ca 30 dB at 1000 GHz (see Fig.4, branch a, slope -14.3 dB/100 GHz). The corresponding conversion loss L of the harmonic mixer ESA-2-FC is typically 48 dB at 700 GHz, and its frequency dependence gives a slope of 3.6 dB/100 GHz. Let us remark that this loss L evolution with frequency, on the ESA-2-FC detection side, is three times slower than the power decrease on the ESA-1-FC source side (-10.7 dB/100 GHz as seen in section I.). For experiments beyond 1 THz, the single-Schottky ESA-2-FC extension could still be used for detection, if the single Schottky multiplier source ESA-1-FC is replaced by dedicated multiplication chains (optimized to generate a single harmonic). With such state-of-the-art chains, the available microwaves can be 20 uW ca 1THz, 1 uW ca 1.7 THz (6). By extrapolating the linear evolution of the loss L of ESA-2-FC observed from 300 to 1000 GHz, one predicts a dynamic range which permits experiments up to 1.8 THz, see Fig.4, branch b.

V. Simultaneous vector detection of two freq uencies from different sources (two multiplication chains).

The dynamic range shown in Fig.4 is a clear indication that dedicated multiplication chains give more comfortable signals above 600 GHz, and are quite necessary above 1 THz. However, contrary to the single-Schottky multipliers, multiplication chains are built for delivering a single frequency. The dual-frequency experiments remain possible with two separate multiplication chains, detected by the previous ESA-2-FC harmonic mixer, which is a single Schottky device, and can detect simultaneously two harmonic mixing ranks Mb and Mb'. These ranks will be, most of the time, successive integers:

$$Mb' = Mb - 1$$

Mb and Mb' can be prime numbers. On the contrary, the multiplication ranks Ma and Ma' cannot be prime numbers, since the multiplication chains combine cascaded doublers and triplers. Possible Ma and Ma' values are: 4, 6, 8, 9, 12, 16, 18, 24... Fig.5 gives the schematic diagram of the two multiplication chains (Gunn A, and Gunn A') detected by the single-Schottky Harmonic Mixer ESA-2-FC (Gunn B). Each Gunn is PLL-controlled so that its frequency is related to the frequency F1 of the 7.4-18.6 GHz centimeter source inside the MVNA, with a harmonic rank K and an offset Fo. For Gunns A, A', B:

$$Fa = Ka\,F1 - Foa$$
$$Fa' = Ka'\,F1 - Foa'$$
$$Fb = Kb\,F1 - Fob$$

The harmonic mixing ranks at detection are Mb for the frequency Fmm coming from the Gunn A after multiplication by Ma, and Mb' for Fmm' coming from Gunn A' multiplied by Ma'. The intermediate frequencies Fvr and Fvr', appearing together at the ESA-2-FC output, obey similar equations. For instance:

$$Fvr = (Ma\,Ka - Mb\,Kb)\,F1 + Mb\,Fob - Ma\,Foa$$

where F1 can be eliminated if:

$$Ma\,Ka = Mb\,Kb$$

and, similarly:

$$Ma'\,Ka' = Mb'\,Kb$$

Practically, one chooses a fixed frequency for Fob (37.5 MHz), the Channel 1 receiver frequency is at Fvr=59.0105 MHz, and the Channel 2 receiver frequency at Fvr'=34.0105 MHz, the offsets Foa and Foa' being generated by synthesizers at frequencies:

$$Foa = (Mb / Ma)\,Fob - Fvr / Ma$$
$$Foa' = (Mb' / Ma')\,Fob - Fvr' / Ma'$$

Preliminary experiments have demonstrated a good behaviour, for several cases (see Table 1), with a crosstalk (detection of Fmm in Channel 2, detection of Fmm' in Channel 1) below -80 dB.

References.

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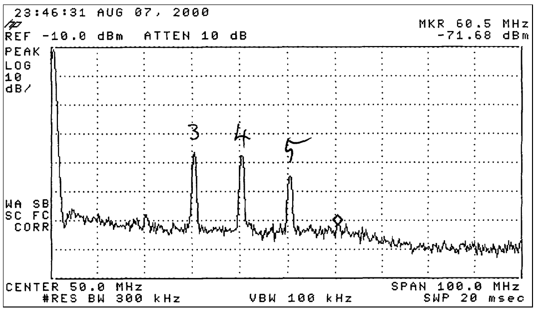

Fig.1.
Vertically : 10dB/div. Horizontally : 10 MHz/div, Span 0-100 MHz. Signal detected by the SIMUHADE with a Gunn at 103 GHz feeding a single-Schottky multi-harmonic multiplier with a F>285 GHz high-pass filter at its output. The successive harmonics M=3-4-5, observed at 30-40-50 MHz, correspond to the microwaves at 309-412-515 GHz.

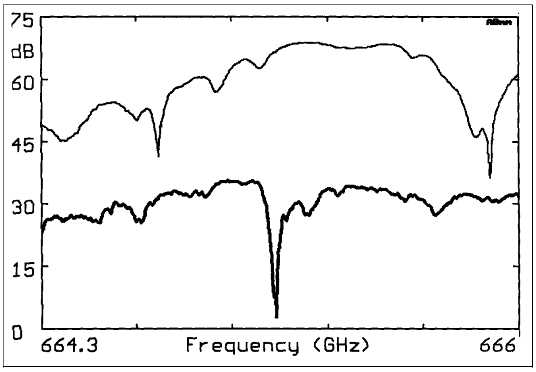

Fig.3.
Search for whispering gallery mode resonances in a quartz disc, 18mm diameter, thickness 1mm. The frequency sweep is operated from 664.3 GHz to 666 GHz on the harmonic M=7 of the multiplier (lower trace, resonance found at 665.1 GHz), and, simultaneously, on the harmonic M=6 of the multiplier, from 569.4 GHz to 570.9 GHz (upper trace, resonances found at 569.8 and 570.8 GHz).

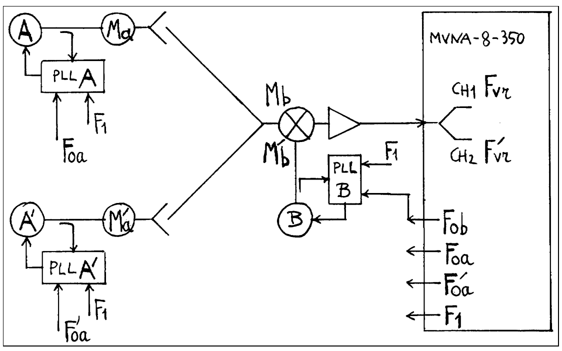

Fig.5.
Experimental setup for dual-frequency detection of two independent multiplication chains.

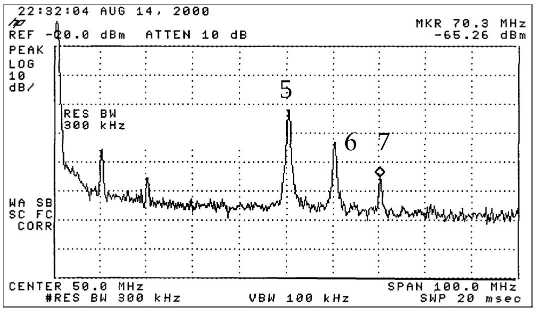

Fig.2.
Same as Fig.1, with a F>475 GHz high-pass filter at the multiplier's output, and a Gunn tuned at 96 GHz. The harmonics M=5-6-7 observed at 50-60-70 MHz, correspond to microwaves at 480-576-676 GHz.

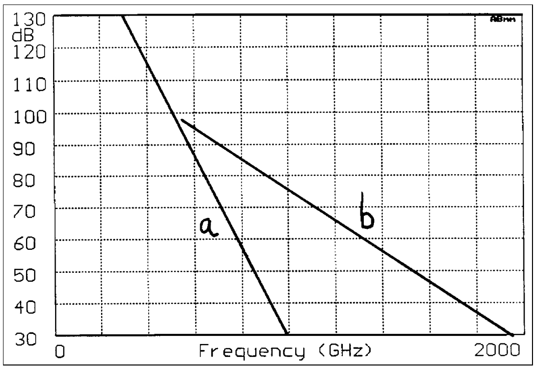

Fig.4.
Dynamic range, MVNA-8-350 with extensions. In a) : observed with a single pair of extensions (source ESA-1-FC, detection ESA-2-FC) covering continuously the interval 250-1000 GHz. In b) : extrapolated from available powers from different multiplication chains, all detected with the single extension ESA-2-FC.

Fmm Fmm' (GHz)	Ma Ma'	Mb Mb'	Fa Fa'	Ka Ka'	Fb	Kb	F1 (GHz)
597 497.5	6 6	6 5	99.5 82.92	6 5	99.5	6	16.58
768 672	8 8	8 7	96 84	8 7	96	8	12
832 936	8 12	8 9	104 78	8 6	104	8	13
1080 990	12 12	12 11	90 82.5	12 11	90	12	7.5

Table 1.
Parameters of the observed pairs of frequencies.