

A Microwave Fourier Transform Spectrometer in the Region from 4 to 6 GHz with Double Resonance Modulation

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Z. Naturforsch. **44a**, 751–755 (1989); received July 8, 1989

We report on the experimental set up and performance of a microwave Fourier transform spectrometer for the G band from 4 to 6 GHz. The sensitivity, achievable linewidth, and resolution capability is demonstrated by measurements of rotational transitions of various molecules.

Introduction

We reported on microwave Fourier transform (MWFT) spectrometers in the region from 5.4 to 40 GHz [1–5]. As it is now proved that this type of microwave spectroscopy is superior to microwave Stark spectroscopy [6–8] by higher sensitivity and resolution we extended the range of our spectrometers. The lower microwave region is interesting for the investigation of nuclear quadrupole hyperfine structure as the splitting of transitions with low angular momentum quantum numbers is generally the largest in a rotational spectrum. Further, the Doppler width is reduced.

Set Up of the Spectrometer

In Fig. 1 we present the set up. For convenience of operation we concentrated most of the equipment on one side of the 12 m long substance cell. In former set ups we avoided this to minimize interference. The units **1**, **20**, **31**, **15**, **3** and **4** form a phase stabilized signal source. The frequency is referred by the receiver **49**, frequency doubler **50** and frequency multiplier **51** to the normal frequency station DCF 77 Mainflingen.

The local oscillator source **2**, **22**, **28**, **29**, **14**, **7**, **13**, **5** is phase stabilized with an offset of +160 or –160 MHz with respect to the signal source as master.

With the power meter **40** the input to the mixer **14** can be controlled. By the attenuators **23** and **24** the

input power for the travelling wave tube amplifier (TWTA) **6** can be adjusted. It is controlled by the power meter **39**. By the PIN switches (1) **34** and (2) **35**, microwave pulses are formed. They are amplified by the TWTA **6**. The isolator **21** shields the TWTA from reflected microwave power. The PIN switch (3) **37** reduces the noise output of the TWTA **6** during the detection period. Together with PIN switch (3) **36**, a leakage of microwave power to the substance cell **47** is reduced. The double balanced mixer (5) **16** introduces a $0^\circ/180^\circ$ phase modulation. This phase alternating pulse sequence (PAPS) [9] reduces coherent perturbing signals. The time diagram of the PIN switches, PAPS and detection is given in Figure 2 of [4].

The amplified microwave pulses are introduced to the substance cell **47** to polarize the molecular ensemble. The isolators **45** and **46** of low VSWR reduce pulse reflections at both ends of the cell. The cell is 12 m long with an inner cross section of $47.55 \cdot 22.15$ mm. It can be cooled to -60°C by a cryostat. Connected to the cell is the usual vacuum equipment. It should be noticed, that the microwave windows are shielded to minimize coherent perturbing signals.

By the PIN switch (4) **38** the detection system **17**, **9**, **11**, **18**, **8**, **33**, **41** is protected from the MW pulses. The band pass filter **17** suppresses harmonics of the experiments repetition rate produced in the PIN switch **38**. The low noise amplifier **9** reduces the over all noise figure of the detection system. For supplying the local oscillator power we had to use a waveguide **48** as a 12 m cable had too much attenuation.

The down converted molecular signal in the region of 160 MHz is processed as in the previously reported spectrometers. It is a second time down converted to the 30 MHz region and recorded by the transient digitizer and averager **43** [10] which is connected to a

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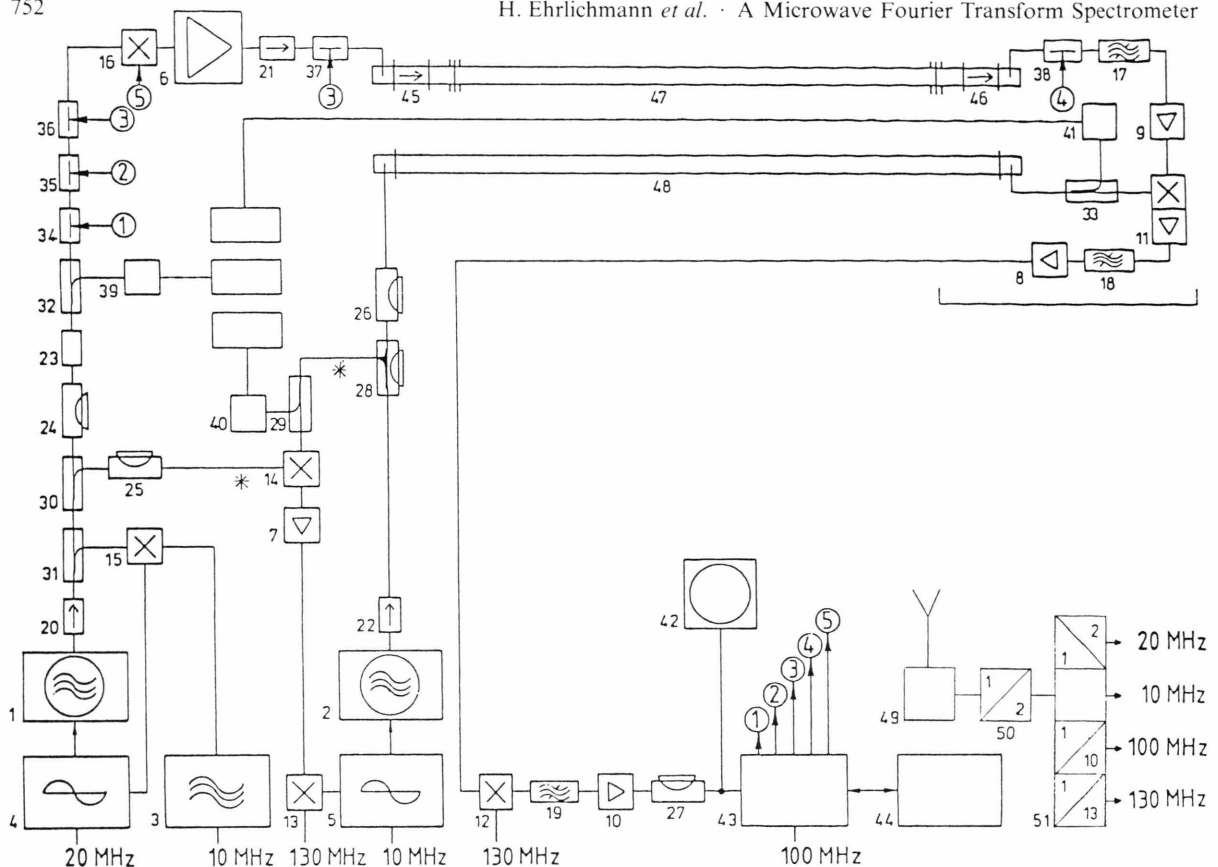
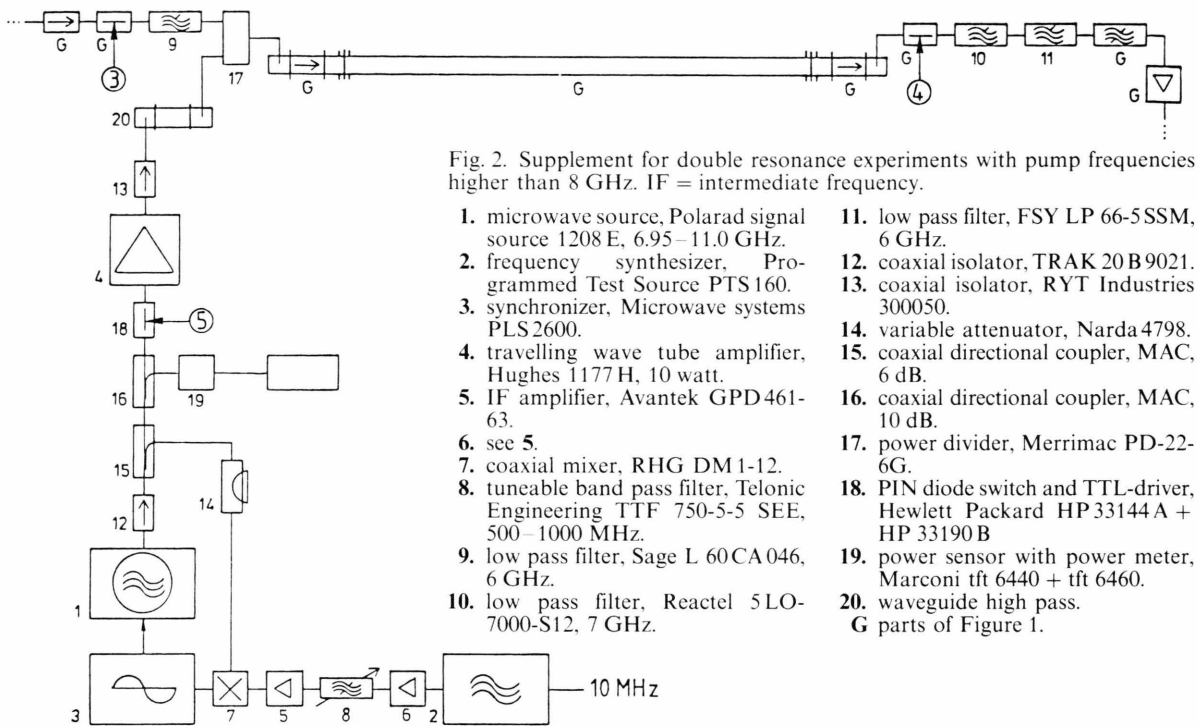


Fig. 1. Detailed setup of a MWFT spectrometer in the range from 4 to 6 GHz (G-band). IF = intermediate frequency, NF = noise figure.

1. microwave source, Hewlett Packard (HP) sweep generator HP 8690 B + HP 8693 A, 4–8 GHz.
2. microwave source, Polarad signal source 1217 E, 3.7–8.4 GHz.
3. signal generator, HP 8656 A, 0.1–990 MHz.
4. synchronizer, HP 8709 A.
5. synchronizer, Schomandl FDS 30.
6. travelling wave tube amplifier, Hughes 1277 H, 20 watt.
7. IF amplifier, RHG ICFV 160601.
8. IF amplifier, RHG ICFH 160LN.
9. microwave amplifier, AvanteK AMT 8034, NF = 3.6 dB.
10. IF amplifier, RHG ICFV 3010.
11. mixer with amplifier, Honeywell Spacecom MPA 0408 1.
12. IF mixer, Mini Circuits ZAD1.
13. see 12.
14. coaxial mixer, RHG DME 4–18.
15. harmonic mixer, Mini Circuits ZAM-42.
16. biphas modulator, RHG DMK 2-18.
17. band pass filter, Filtronics F10345, 4–8 GHz.
18. band pass filter, Lark SF 160-50-B/B, 160 MHz.
19. band pass filter, FSY BR 30-10-4 BMB, 30 MHz.
20. coaxial isolator, SMT C 4080.
21. coaxial isolator, Mikrotek H40C80 A0.
22. coaxial isolator, P & H C1-C226314.
23. attenuator, Suhner, 10 dB.
24. variable attenuator, Narda 4799.
25. variable attenuator, Engelmann A 804 N.
26. variable attenuator, Narda 729 FM.
27. variable attenuator, HP 355 C VHF.
28. probe coupler, Narda 3080.
29. coaxial directional coupler, Narda 4014 C-30 dB.
30. coaxial directional coupler, MAC C 3205-10, 10 dB.
31. coaxial directional coupler, DCS108, 10 dB.
32. coaxial directional coupler, AEL 10200, 20 dB.
33. coaxial directional coupler, Narda 3004-20, 20 dB.
34. PIN diode switch and TTL-driver, HP 33144 A + HP 33190 B.
35. see 34.
36. see 34.
37. see 34.
38. see 34.
39. power sensor with power meter, HP 8478 B + HP 432 A.
40. see 39.
41. see 39.
42. oscilloscope, Tektronix 2213 A.
43. averager and control system [10].
44. personal computer, Tandon PCA 20.
45. waveguide isolator, Pamtech GHG 2001.
46. see 45.
47. sample cell.
48. waveguide.
49. frequency standard, 5 MHz, and receiver, Rohde & Schwarz R&S XSD 2 + R&S XKE 2.
50. frequency doubler.
51. frequency multiplier.

* position of optional coaxial isolators to reduce coherent perturbing signals.



personal computer 44 for additional averaging and data handling.

Supplement for Double Resonance

With the set up of Fig. 2 the spectrometer of Fig. 1 can be used for double resonance experiments with the signal radiation in the G band 4 to 6 GHz and the pump radiation in the X band 8 to 12.4 GHz or higher.

The phase stabilized pump source is built with the units 1, 12, 15, 14, 7, 3. The synthesizer 2 provides the reference. Its output frequency is multiplied by overdriving the amplifier 6. The tuneable band pass filter 8 selects the harmonic. The input power for the TWTA 4 is monitored by the power meter 19 via the directional coupler 16.

Generally we use the modulation technique described in [11]. The PIN switch (5) 18 is used for modulation. During a modulated double resonance experiment the biphas modulator 16 of Figure 1 is kept in one phase. If the PIN switch 18 is permanently open, continuous wave double resonance experiments of the kind described in [12] can be performed.

The high pass filter 20, a piece of X-band waveguide with a cut off of 6.56 GHz, protects the pump branch whereas the low pass filter 9 shields the signal branch from the pump power. The low pass filter 10 together with the low pass filter 11 protects the detection system from the pump power.

Performance of the Spectrometer

We used the spectrometer in the range from 3.8 to 7 GHz. The line width and resolution, which can be obtained, is illustrated in Figs. 3 and 4. Figure 3 shows the $J = 25, v_2 = 1$ l -type transition of OCS with a half width of 6.6 kHz at half height in the power spectrum. The Doppler width is $\Delta\nu_D = 3$ kHz. The wall collision broadening is $\Delta\nu_W = 1.6$ kHz. Figure 4 presents the transition $J, K_-, K_+ - J', K'_-, K'_+ = 15, 11, 4 - 15, 11, 5$ or morpholin D equatorial [13] showing ^{14}N and D hyperfine structure. The splitting of the largest components is 23 kHz. The limit of resolution is about 13 kHz as shown in Fig. 1 of [14]. This value resulted from the decay fit [15] by which we always analyze narrow multiplets to minimize overlapping effects. In Fig. 5 we show a test of the sensitivity by the l -type

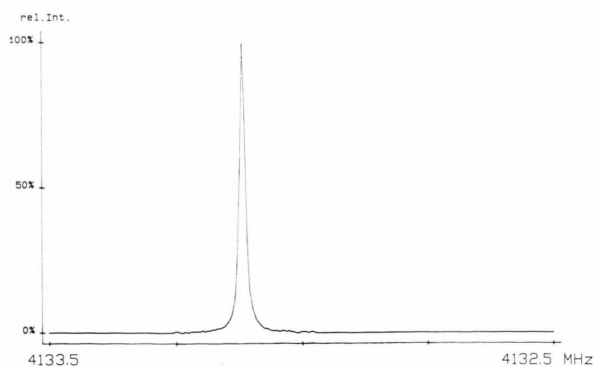


Fig. 3. *l*-type transition of OCS, $J = 25$, $v_2 = 1$ at 4133.119 MHz, temperature 250 K, pressure 2 mTorr (0.3 Pa), power spectrum, sample interval 50 ns, 4096 data points in the time domain, $1.6 \cdot 10^6$ experiment cycles, spectral point distance 4.9 kHz.

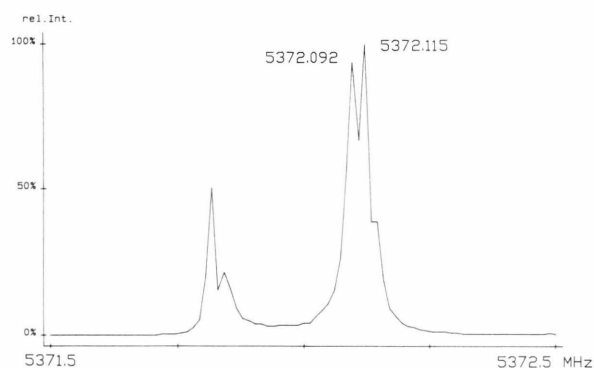


Fig. 4. Transition $J, K_-, K_+ - J', K'_-, K'_+ = 15, 11, 4 - 15, 11, 5$ of morpholin D equatorial near 5372.0 MHz with hyperfine structure of ^{14}N and D, temperature 220 K, pressure 2 mTorr (0.3 Pa), power spectrum, sample interval 20 ns, 4096 data points, $3.2 \cdot 10^6$ experiment cycles, spectral point distance 12.2 kHz.

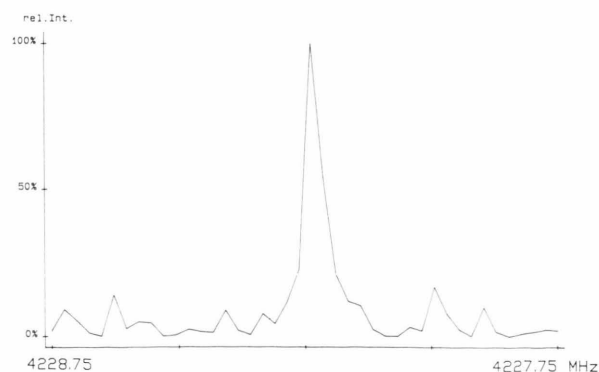


Fig. 5. *l*-type transition of O^{13}CS , $J = 25$, $v_2 = 1$ in natural abundance, absorption coefficient $\gamma_{\text{max}} = 2 \cdot 10^{-11} \text{ cm}^{-1}$, temperature 250 K, pressure 4 mTorr (0.5 Pa), power spectrum, sample interval 10 ns, 4096 data points, $89 \cdot 10^6$ experiment cycles, spectral point distance 24.4 kHz.

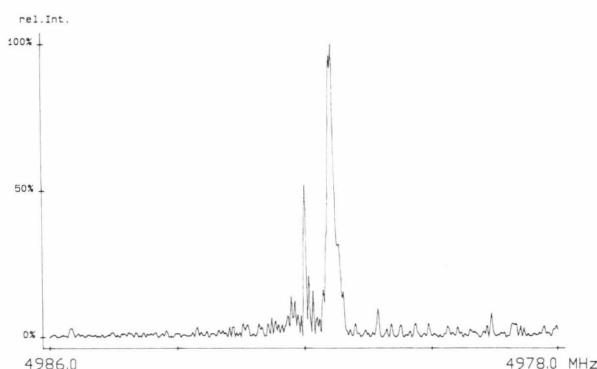
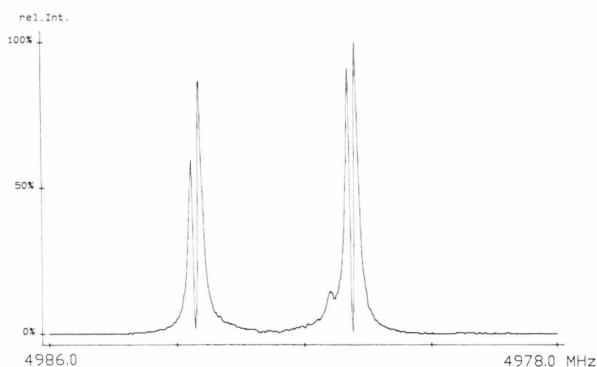


Fig. 6. Double resonance search for the transition $J, K_-, K_+ - J', K'_-, K'_+ = 1, 0, 1, 5/2 - 0, 0, 0, 3/2$ of cyclopropylbromide- ^{81}Br . Temperature 220 K, pressure 3 mTorr (0.4 Pa), power spectrum.

a) upper trace: Without pump radiation, sample interval 20 ns, 1024 data points, $1.28 \cdot 10^6$ experiment cycles.

b) lower trace: With pumping of $2, 0, 2, 7/2 - 1, 0, 1, 5/2$ at 10060 MHz, $2.56 \cdot 10^6$ experiment cycles, other conditions unchanged.

transition of O^{13}CS $J = 25$, $v_2 = 1$ with an absorption coefficient [16] of $\gamma_{\text{max}} = 2 \cdot 10^{-11} \text{ cm}^{-1}$. It was measured in about 400 sec. with 4096 data points of the time domain signal.

The double resonance effect is presented in Figures 6a, b. In the upper trace the region from 4978 to 4986 MHz of the rotational spectrum of cyclopropylbromide- ^{81}Br is recorded, where the component $F - F' = 5/2 - 3/2$ of the $J, K_-, K_+ - J', K'_-, K'_+ = 1, 0, 1 - 0, 0, 0$ transition is expected. The lower trace with double resonance modulation by the component $7/2 - 5/2$ of the transition $2, 0, 2 - 1, 0, 1$ pumped at 10060 MHz verifies that the shoulder in the upper trace is the component sought after. A coherent perturbation is also to be seen.

The spectrometer was used for the investigation of the rotational spectra of methylazide [17], deuterio-

isocyanic acid [14], t-butylbromide, ethylisocyanide, morpholine, nitrobenzene, piperidine, n-propylisocyanide, pyrrolidine, sulfurdichloride and others [18].

In general we can state that the spectrometer is a very valuable instrument especially for the investigation of hfs-structures. In addition, the density of rotational spectra reduces with lower frequencies, which helps assignment.

Acknowledgement

We thank the members of our group for help and discussion, the members of our workshop for manufacturing many microwave parts and the Deutsche Forschungsgemeinschaft, the Land Schleswig-Holstein, and the Fonds der Chemie for funds.

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