PRECISE MEASUREMENTS IN MILLIMETER AND SUBMILLIMETER-WAVE RANGE BASED ON PHASE-LOCKED PRIMARY RADIATION SOURCES

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Exclusive kind of microwave radiation generators continuously covering whole millimeter and submillimeter wave range are backward wave oscillator (BWO) tubes. Series of such tubes was developed by Golant with coauthors [1] in sixties and now are commercially available from "Istok" (Fryazino, Moscow region). The report is devoted to a new developments of phase lock loop (PLL) kind of frequency stabilization systems for these sources in the range up to beyond Terahertz as well as application of these systems for scientific and technical measurements.

The operation of the first PLL stabilization system of millimeter and submillimeter-wave BWOs of kind of [1] in the range up to 350 GHz was demonstrated by our group in 1970 [2]. Then the operation range of the system was extended by steps up to 500 GHz in 1976 [3], up to 600 GHz in 1979 [4], up to 820 GHz in 1984 [5]. Next considerable step towards high frequency range we made after joint development with Institute of Electronic Measurements "Kvarz" (Nizhny Novgorod) of series of commercial millimeter-wave frequency synthesizers covering all together the range 35-178 GHz [6]. The synthesizers are based on BWOs of kind of [1] stabilized by PLL system against stable radio signal. The synthesizers were used as source of reference radiation for stabilization of submillimeter-wave tubes as well as primary radiation sources. In 1994 working in collaboration with Cologne's University (Germany) we introduced the BWO PLL system operating up to 970 GHz [7]. Later the range of the setup was extended up to the range of highest frequency tube - 1267 GHz [8-10]. Block-diagram of the system is presented in Fig.1.

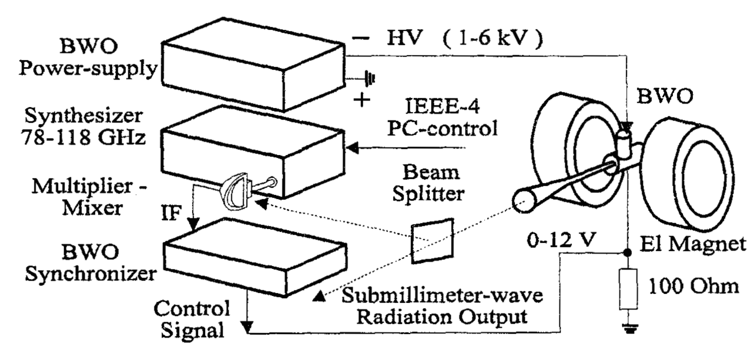

Fig. 1. Block-diagram of submillimeter wave frequency synthesizer.

The system performs stabilization of sumbillimeter-wave source radiation frequency against harmonic of radiation of millimeter-wave synthesizer, so function of controlling of the source is passed to the synthesizer. The synthesizer is one of the crucial part of the system since the basic properties of output submillimeter-wave radiation such as spectrum purity and bandwidth, frequency stability and accuracy, scanning abilities and step-width etc. are determined by corresponding properties of the synthesizer but multiplied by number of harmonic used for the PLL stabilization. The synthesizer and consequently output submillimeter-wave radiation is computer controlled through standard GPIB interface. Another crucial element of the system is specially developed in our laboratory broad-band quasi-optical multiplier-mixer. The multiplier-mixer consists of a planar Schottky diode, mounted at the end of ridged 3-millimeter waveguide. The diode is placed in the focal point of a semiparabolic mirror illuminated by submillimeter-wave radiation. Once the mixer is properly adjusted, no further tuning is required. Construction of the mixer is shown in Fig. 2.

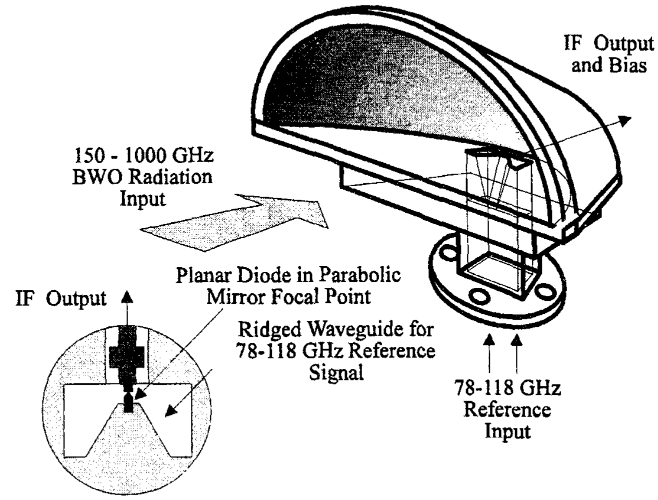

Fig. 2. Broad-band multiplier-mixer for submillimeter-wave range.

Synchronizer includes low noise intermediate frequency amplifier, phase sensitive detector, output amplifier and serving electronics. For the first time this system was installed and used for the high resolution spectroscopy at Cologne's University (Germany) and later spread all over the world from Canada, to Japan. A sub-Doppler spectral resolution, a few kilohertz accuracy of frequency measurements, availability of non-stop single frequency scan length up to 200 GHz with a minimum step of 500 Hz, were demonstrated [7-10]. At present time the spectrometer has highest performance in the world.

Similar but a bit different approach to output radiation control we used developing the laboratory prototype of commercial frequency synthesizer in the range 178 - 370 GHz (covered by two BWOs of corresponding range). The device is designed by analogy with, and as continuation of aforementioned series of "Kvarz" synthesizers [6]. Block-diagram of the device is presented in Fig. 3.

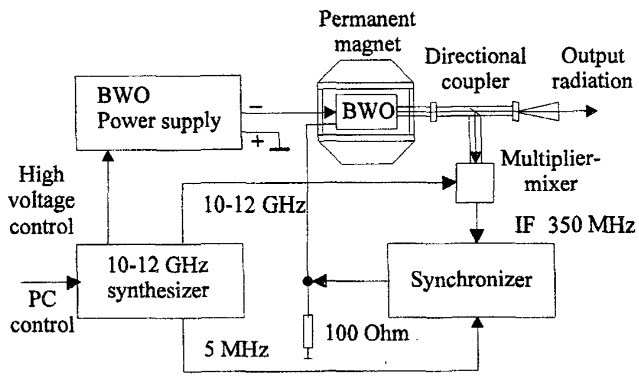

Fig. 3. Block-diagram of 178-370 GHz frequency synthesizer.

Three previous examples demonstrate as frequency stabilization of radiation source leads to development of high precision frequency measurements. Two following examples shows that use of precise frequency methods allows to perform precise "amplitude" measurements.

While working on BWO radiation frequency multiplication [13] and having precisely controlled by use of PLL system source of radiation in the range of 1-3 mm we developed universal method of measurement of conversion losses for every separate harmonic with numbers from 2 to 5 produced and radiated by multiplier. The method is based on measurement of absorption of radiation in spectral lines with known intensity and acoustic detection of this absorption. Block-diagram of the experiment is shown in Fig. 5.

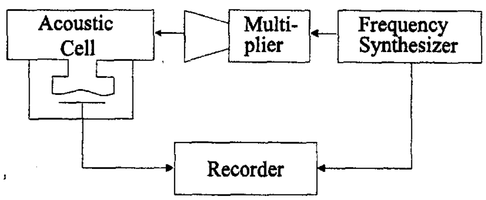

Fig. 5. Block-diagram of radiation frequency multiplication experiments.

The radiation of the source passed through the multiplier and containing both fundamental radiation and harmonics is directed into acoustic gas cell (radio-acoustic detector [4]) commonly used in our spectroscopic experiments. The cell is filled by gas with well known spectrum. Observed spectral lines are recorded and analyzed by PC. Following properties of the acoustic detector in addition to its high sensitivity make it crucial element of the method: i) sensitivity of radio-acoustic detector is independent from frequency range, polarization and space mode of the radiation; ii) there is no signal from the acoustic detector if there is no absorption in the spectral line of gas inside the cell; iii) output signal has linear dependence from the radiation power which was absorbed inside the gas cell. Thus a minor power of a few nanowatt at any particular harmonic may be detected in spite of the fact that at the same time hundreds of milliwatt of fundamental power and other harmonics are passing through the cell but do not produce any signal. So spectral lines of the gas are that frequency-selective element which allows us to distinguish one harmonic from another and those from fundamental. The main criterion of identification of observed line is coincidence of its frequency with calculated line frequency taken from the spectrum data base. The use of PLL stabilization of the fundamental radiation source supports the method with so high accuracy of line frequency measurement that the line identification is undoubted. The observed spectral line width is an additional criterion for the line identification. Due to the principal of lines observation the frequency step of radiation scanning through a range is determined by frequency step of fundamental radiation, but for radiation on harmonics the value of the step should be multiplied by corresponding harmonic number. So if higher is the harmonic number then narrower is the linewidth of observed line. The amplitude of observed line is in direct proportion to the line intensity (except the case of too strong absorption which can be estimated beforehand) and to the power of radiation. So comparison of amplitude of observed lines with known intensities allows us to perform quantitative comparison of power in different harmonics. In particular such important characteristic of multiplier as conversion losses can be determined. Dynamic range of such measurements is limited by the acoustic sell sensitivity and in our experiment it was about 55 dB. Accuracy of the method is limited by variation of power of radiation inside the acoustic cell due to parasitic interference when frequency of radiation is changed from one line to another. In our experiments the accuracy of measurements was about 20%. Use of this method for the first time gave possibility in real time to make tuning and ajusting of submillimeter-wave multipliers at every harmonic.

Computer controlled and stabilized by PLL system microwave source of radiation in combination with spectral line shape processing software and Fabry-Perot cavity with quality factor more than 600000 helped us to develop method of ultralow absorption measurements in dielectrics [14]. Open Fabry-Perot resonators are uniquely suitable for studying dielectric properties of low-loss materials. The absorption measurements in this case comes to measurements of quality factor of the empty and loaded resonator. There is a sufficient variety of measurement and calculation techniques to obtain a dielectric properties of gas, liquid and solid samples but in

Conventional BWO tube from Istok of kind of OB-24 or OB-30 is placed in a compact permanent magnet system. The output radiation of the tube is stabilized by PLL system against harmonic of 10-12 GHz signal. This signal is generated by base block of "Kvarz" synthesizer which is in fact precise frequency synthesizer of this range. The base block produces also a signal for the BWO power supply to address the radiation of the tube to required frequency range where it will be automatically caught and locked by PLL system. Further precise control of the tube output radiation is performed by controlling of the 10-12 GHz signal of the base block by PC through GPIB interface. The multiplier-mixer is of balance type based on couple of planar Schottky diodes glued on a fin-line inside a 3-millimeter wave-guide. The synchronizer is of the same kind as we use for stabilization of submillimeter-wave BWOs. Workability of the synthesizer in such configuration was demonstrated up to 500 GHz. Main parameters of the synthesizer output radiation are following: relative frequency stability - 10^{-8} with inner quartz reference oscillator and 10^{-11} with use of external 5 MHz signal from rubidium standard; radiation bandwidth - 1 kHz; minimal frequency step 100 Hz.; output power 5-50 mW (depending from BWO output). The synthesizer was successfully used for high resolution spectroscopy [11].

In close collaboration with spectroscopy group of Lille's University (France) the aforenamed PLL technique developed for frequency stabilization of BWOs was successfully used for stabilization of continuous wave far infrared laser. The preliminary work done in this direction is described in ref. [12]. The FIR laser working in the range 0.6 - 2.5 THz and serving as radiation source in sideband spectrometer was for the first time stabilized against harmonic of 78-118 GHz synthesizer. Block-diagram of the setup is presented in Fig.4.

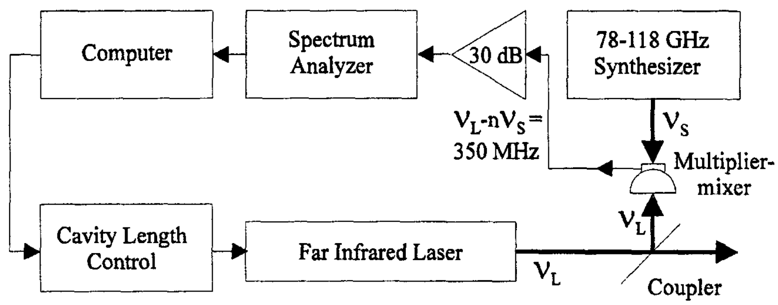

Fig. 4. Block-diagram of FIR laser stabilization.

Minor part of laser radiation is split and mixed with radiation of 78-118 synthesizer by quasi-optical multiplier-mixer of the same kind as described above. The beat-note signal at frequency 350 MHz after low noise preamplifier is analyzed by commercial HP spectrum analyzer. For the laser stabilization achievement we used two facts. First, that internal frequency-meter of the analyzer allows to measure frequency of beat-note signal in a "marker tracking" mode with accuracy 1 kHz, and second that the full information about the beat-note signal may be in real time transferred to computer through GPIB interface. The computer in a real time processes the information and through fast GPIB card and special interface controls micro-step motor. The motor changes the laser cavity length and consequently frequency of radiation of the laser by such way that frequency of beat-note signal remains constant. As it's seen, such stabilization is not of PLL kind but just ordinary so called frequency stabilization, when the system reacts in proportion to frequency difference between stable reference signal and signal which has to be stabilized, so the frequency of the last one is constant only in average. Nevertheless in such frequency lock loop we achieved the frequency stability of the laser radiation better than 50 kHz Such good result became possible due to the fact that emission of the laser itself has narrow bandwidth and is quite stable in a short time but its frequency is slowly drifting due to temperature effects which can be easy eliminated by our stabilization system. Advantage of our system in comparison with other systems with frequency stabilization loop is - it doesn't need frequency modulation of the laser radiation. The stabilization increased accuracy of frequency measurements of the spectrometer in about order of magnitude.

any case all the information about absorption is contained in a broadening of resonance width of loaded resonator in comparison with the empty one. For achieving the highest sensitivity of absorption measurements, the highest quality factor of the resonator together with precise method of the resonance curve width measurements should be developed. In course of the work we concentrated on increase signal-to-noise ratio, optimization of radiation source and resonator geometry, coupling, detection and signal processing. Special work had been performed to reach the highest possible quality factor of the cavity. We minimized coupling, diffraction and atmospheric losses and maximized the reflection coefficient of mirrors. Quality from 560000 up to 670000 depending from working frequencies and different resonator geometries (which is practical limit of the quality factor of the Fabry-Perot resonator with non-cooled mirrors) has been achieved. To increase signal-to-noise ratio we used 100% amplitude modulation of radiation, selective amplifier at the modulation frequency and synchronous detection of the signal from detector as well as data accumulation and long time averaging. The software used in this measurements was developed earlier for precise studies of molecular collisional broadening. Block-diagram of the experiment is given in Fig.6.

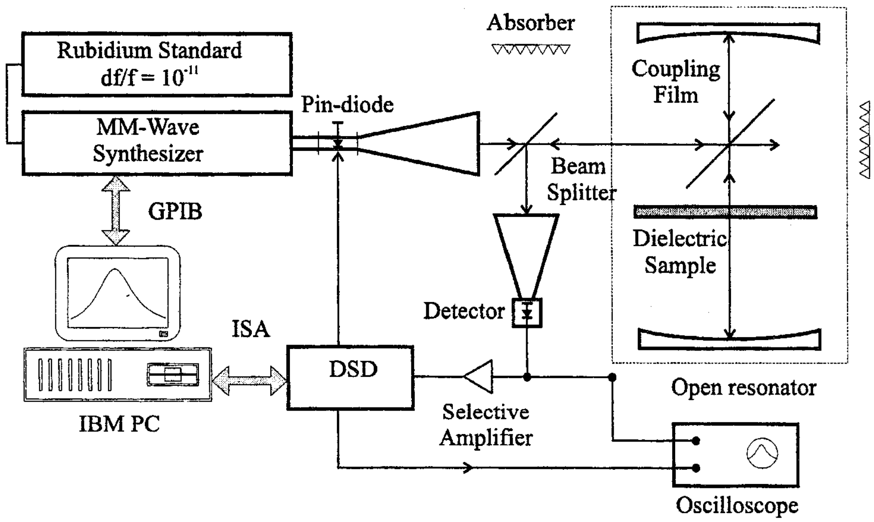

Fig. 6. Block-diagram of ultralow absorption measurements in dielectrics.

"Kvarz" microwave synthesizer [6] of 78-118 GHz range is used as source of radiation . The resonator is connected with synthesizer and detector by quasioptical 3 dB splitter. Amplitude modulation of the synthesizer radiation is made by pin-diode. The teflon film placed under 45 degrees angle to the resonator axis serves for coupling the resonator. A plane parallel sample of a dielectric is placed in the center of the resonator perpendicular to its axis. Computer controls the synthesizer scanning step-by-step over frequency range of resonance band of the resonator and for each step captures the amplitude of the signal from detector. Digital synchronous detector (DSD) mounted in plug-in PC board was used for data acquisition. Resonance curve obtained by such way was fitted to the Lorentzian profile by least-squares method.

After optimization of experimental conditions the absolute accuracy of measurement of the cavity respond width was increased up to 500 Hz at 110 GHz frequency of radiation. Total measurement time was 130 sec. (15 resonance curve records). The limit sensitivity recalculated from such accuracy corresponds to the loss tangent less than 10^{-8} minimal detectable absorption for case of completely filled by dielectric cavity. Counting in absolute units it means that absorption of 0.1 dB/km can be detected by use of Fabry-Perot resonator of 300 millimeter length. For the interpretation of obtained accuracy in terms of absorption measurement in solid or liquid dielectric sample situated in the resonator a real case must be considered. We used the method when a plane-parallel dielectric placed in the resonator perpendicular to its axis has "resonant" optical thickness: i.e. constituting exactly integer number of half wavelengths at one of the resonator eigenfrequencies. In this case rather simple expressions for calculation of loss tangent from experimental data may be used [15]. The condition of "resonant" thickness can be easy obtained by tuning the synthesizer frequency. Then assuming 10% of standard deviation of measurement error (what corresponds to about 7 kHz resonance curve difference of loaded and empty resonator) we get following loss tangent values: $6.9 \cdot 10^{-7}$ for sapphire plate and $5.5 \cdot 10^{-7}$ for silicon plate both of about 3 mm thickness and $6 \cdot 10^{-6}$ for diamond plate of thickness 0.57 mm. (This estimation is made for materials and their thicknesses practically used for windows of powerful gyrotrons.) Such accuracy is more than sufficient for loss tangent measurements at the present state of low-loss materials development.

The achieved level of sensitivity exceeds the one obtained earlier by more than two orders. The method can be used not only for gyrotron output windows analysis (the problem of developing of ultralow absorbing windows was mentioned as the main difficulty at the creation of 1 MW CW gyrotrons) but for diagnostics of high purity semiconductors, for measurements of thin films properties, for investigation of absorption temperature dependencies etc.

The same method may be used for precise measurements of radiation reflection coefficient from highly reflective surfaces.

Although the experiment was made in 3 millimeter-wave range, similar technics exist up to frequencies exceeding 1 THz, so described measurements are affordable at the whole millimeter and submillimeter wave bands.

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