Hilbert spectroscopy based on the ac Josephson effect for liquid identification

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Abstract. Fast and reliable identification of liquids is of great importance in developing new security measures at public places. A concept of liquid identification is presented, based on our Hilbert spectroscopy and high-Tc Josephson junctions, that can operate at the frequency range of main dispersions of liquids under concern, i.e. at the intermediate range from microwaves to terahertz frequencies. Several demonstration setups, consisting of synthesized polychromatic radiation sources and compact Hilbert spectrometers integrated in Stirling coolers, have been developed and characterized. Reflection polychromatic spectra of various bottled liquids have been measured at the spectral range of 15 – 400 GHz with total scanning time down to 0.5 second and the possibility of reliable identification of liquids has been demonstrated.

1. Introduction

Due to extremely low noise, low power dissipation, low intrinsic characteristic time constants and high dynamic power range, superconducting detectors of electromagnetic radiation have already demonstrated applicability in infrared single-photon counters [1], millimeter-wave and terahertz heterodyne mixers for radioastronomy [2, 3]. Recent interest in improvement of public security screening has stimulated a development of first terahertz imaging arrays [4, 5], where low-Tc Nb superconducting tunnel junctions and microbolometers, developed previously for applications in radioastronomy, were tested. All these results are obtained using low-Tc superconducting detectors at operating temperatures of 0.3 - 4.2 K.

The level of thermal background radiation in security screening is rather high and application of high-Tc Josephson detectors for this purpose seems to be more adequate. Additionally, the higher operating temperatures of high-Tc detectors could make it possible to use well-developed one-stage cryocoolers, which were developed for the cooling of semiconducting imaging arrays. First results concerning the application of high-Tc Josephson detectors in passive millimeter-wave [6] and active terahertz [7] imagers have been presented, aiming to the field of security screening. The high-Tc Josephson junctions of interface-engineered ramp type at 50 K [6] and step-edge type at 10 K [7] were used in the experiments. Only few low-contrast images have been demonstrated with comments on low junction quality and high noise level during the measurements [6, 7].

We have recently presented our results in developing high-quality high-Tc bicrystal Josephson junctions for square-law detection and Hilbert spectroscopy and attracted attention to a great potential of our high-Tc Josephson technology in security applications [8]. A concept of identification of
dangerous liquids by Hilbert spectroscopy, based on high-$T_c$ Josephson junctions, has been suggested for application in security screening [9].

Here, we discuss our concept of liquid identification, pointing out the requirements for the high-$T_c$ junctions and operating conditions, present the results of development of corresponding hardware for a Hilbert spectrometer, demonstrate the results of spectral measurements for polychromatic radiation sources and reflectance from some liquids.

2. Concept of liquid identification

Fast and reliable identification of bottled liquids became a hot issue after uncovered terrorist plot involving the mid-flight detonation of liquid explosives [10]. In addition to conventional X-ray and metal detectors at airport gates, a specific screening of passenger’s luggage is required to find and identify the liquids of concern, which might be dangerous themselves or could be used as components for fabrication of explosives. Typical airport security gate with X-ray and metal detectors has a maximum throughput of about 200 persons per hour and that means that around 18 seconds are already required for each person. So, additional screening of bottled liquids should be very fast and be made without wasting time for opening the cap of bottles.

Among various discussed detection techniques, the technique using electromagnetic radiation is considered as one of the most promising [11]. Reliable identification of liquids with low false alarms, in principle, could be made by electromagnetic measurements of their dielectric functions at the frequency range of their main dispersions [8]. Specific dispersion in the dielectric functions of liquids is reproduced in their reflection spectra, which might be measured by some spectroscopic technique. Reflection spectra calculated for various liquids [9] are presented in figure 1. The differences in reflectance values for practically all pure liquids are relatively high, but for water and hydrogen peroxide this difference is only of few percents. To resolve this difference in reflectance measurements of water and hydrogen peroxide a signal/noise ratio of better than $10^2$ is required.

It also follows from figure 1 that the spectral range of dispersion for presented liquids is rather broad. This frequency range, from a few GHz to a few THz, was not covered by any single conventional spectroscopic technique. Only our Hilbert spectroscopy, based on the ac Josephson effect in high-$T_c$ junctions, has demonstrated applicability at this intermediate frequency range [12-14].

![Figure 1. Reflection spectra for various liquids [9].](image)

The principles of Hilbert spectroscopy are presented elsewhere [15, 16]. The technique is based on analytical properties of a voltage dependence of a response $\Delta I(V)$ of a Josephson junction to external electromagnetic radiation. When weak external monochromatic signal is applied to a Josephson junction, Josephson frequencies $f_j = 2eV/h$ are pulled to the frequency $f$ of the external signal. The result of this frequency pulling is reflected on the dc current-voltage characteristics so, that the
response $\Delta I(V)$, i.e. a difference between the $I(V)$ curve, modified by the electromagnetic signal, and the unmodified $I_{dc}(V)$ curve, demonstrates an odd-symmetric resonance around the voltage $V = h/2e$ and a square-law dependence on the amplitude of the external signal [17]. Thus, a Josephson junction can be considered as a square-law frequency-selective detector.

In more general case of an arbitrary spectrum $S(f)$ of the external signal, the response function $H(V) \propto \Delta I(V) - R(I)V$ was found to be proportional to the Hilbert transform of the spectrum $S(f)$ [15]. Applying an inverse Hilbert transformation to the measured response $H(V)$, the spectrum $S(f)$ can be recovered as [15]

$$S(f) \propto \left(\frac{1}{\pi}\right) \int_{-\infty}^{\infty} \frac{H(f_j) \cdot df_j}{f_j - f},$$

where $P$ is the Cauchy principal value of the integral. First review devoted to our development of Hilbert spectroscopy with high-$T_c$ Josephson junctions was published in 2001 [16].

A frequency-selective response of high-$T_c$ Josephson junctions demonstrates a frequency bandwidth of almost two decades at a junction temperature $T_c$ close to the critical temperature $T_{c}[13]$ and the center frequency of this bandwidth scales with the $I_R(T)$-product of Josephson junction, where $I_c$ is the critical current and $R_n$ is the normal-state resistance of the junction [12, 14]. These circumstances allow us to adjust the spectral range of the Josephson detector to the spectral range where liquids of concern show main dispersion. The frequency range of these measurements might be limited to frequencies below 1 THz due to an increase of absorption in glass or plastic bottles at higher frequencies [8]. So, the frequency range from 5-10 GHz to 500-1000 GHz can be considered for realization of liquid identifier based on high-$T_c$ Josephson junctions and Hilbert spectroscopy.

There are two additional important features, which square-law frequency-selective high-$T_c$ Josephson detectors demonstrate. Their intrinsic sensitivity to millimeter-wave and terahertz electromagnetic radiation is very high and the response $\Delta I$ demonstrates a linear dependence on input signal power $P_{in}$ in a very broad range of $P_{in}$. Quantitatively, the values of intrinsic noise-equivalent power (NEP) of high-$T_c$ Josephson detector was measured as low as $8 \times 10^{-15}$ W/Hz$^{1/2}$ and a power dynamic range $D = P_{in}/(\text{NEP} \cdot \Delta F^{1/2})$ - as high as $2 \cdot 10^7$ for a postdetection bandwidth $\Delta F = 1$ Hz even, when a high-$T_c$ Josephson detector was kept at rather high temperature of 80 K [18]. The high values of the dynamic range $D$ are of importance, when a detector is intended for high-speed measurements, because a large postdetection bandwidth $\Delta F$, say of 1 MHz, will be required and the resulting dynamic range will be of $2 \cdot 10^7$, i.e. three orders lower, than at $\Delta F = 1$ Hz. Due to this high dynamic range of high-$T_c$ Josephson detectors it was possible to measure radiation spectra of pulsed sources in a time interval of a few milliseconds [19].

Based on our previous experience in Hilbert spectroscopy, the conceptual scheme of a demonstrator of liquid identifier was suggested and previously presented [9]. It can be divided into the following components: Hilbert spectrometer with a high-$T_c$ Josephson detector and analogue electronics in a Stirling cooler, a pulsed radiation source, a radiation coupling unit between the source, Hilbert spectrometer and a bottle with liquid, as well as a data acquisition system and a computer with application-oriented software.

3. Hilbert spectrometer

3.1. Stirling cryocoolers

Since 1999 [22], we have gained a lot of experience in integrating high-$T_c$ Josephson junctions into a Stirling cooler SL200 from AIM Infrarot Module GmbH. The cooler has a quite powerful compressor of 100 W and a cooling power of 2.5 W at 80K. It is intended to cool down infrared imaging arrays with corresponding electronics. We have started with this cryocooler and developed a demonstrator of the Hilbert spectrometer.
Recently, a Stirling cooler LSF9589 from Thales Cryogenics B.V. appeared in the market, which has approximately the same values of input electrical and cooling power, but is more compact and has twice less weight, than the cryocooler SL200, which we used before. We have tested both cryocoolers as cryogenic environment for our Hilbert spectrometers. Two developed Hilbert spectrometers are presented in figure 2, the one - with SL200 (left), and the other – with LSF9589 (right).

![Figure 2. Two demonstrators of Hilbert spectrometers integrated with Stirling coolers SL200 (left) and LSF9589 (right). A 30cm-long ruler is used as a characteristic scale.](image)

Each cryocooler itself consists from a compressor, a pressure-transferring line and a separate part with a coldfinger. Each cryocooler is integrated into a 3D-frame made from Al-profiles. A sample holder with the Josephson detector was attached to the coldfinger and was supplied with a thermometer and a heater. The coldfinger is surrounded by a vacuum dewar with a window. A high-density polyethylene wedge window and a horn with a profiled inner surface made of microwave radiation adsorbing epoxy were used to suppress standing waves.

Interference noise can severely deteriorate both spectral resolution and responsivity of the Josephson detector, so special measures were taken to reduce an influence of the electromagnetic field of the cryocooler compressor on the Josephson junction. The compressor of the cryocooler was surrounded by a cryoperm magnetic shield. Excess heat from the compressor and the separate part with the coldfinger was removed by dc-driven blowers integrated in the frame. In addition, the grain boundary of the Josephson junction was positioned perpendicular to the magnetic fields produced by the compressor and moving piston in the cryocooler. With these measures, the linewidth of Josephson oscillation and the responsivity of Josephson detector corresponded to the theoretical limits, determined by thermal fluctuations, even for the junctions with a very low normal-state resistance of 0.2 Ohm.

Using both types of cryocoolers we have developed two demonstrators of Hilbert spectrometers, which are similar in main operating conditions, but the version with LSF9589 is more compact and produces less acoustic noise, than the one with SL200.

### 3.2. Frequency-selective high-$T_c$ Josephson detector

To fit the spectral range of a frequency-selective Josephson detector to the range from 10 GHz to 1 THz, the high-$T_c$ junctions with quite low values of the $I_R R_n$-product of the order of 100 μV are required. We have fabricated [001]-tilt YBa$_2$Cu$_3$O$_{x-}$ bicrystal junctions for our experiments, because this type of junctions [20] demonstrate much lower values of the $I_R R_n$-product, compared with our [100]-tilt junctions [21]. Furthermore, instead of our conventional NdGaO$_3$ bicrystal substrates, we have used the 2x12° MgO substrates that allowed us to fabricate the Josephson junctions with $I_R$-products of 100-250 μV at the temperatures of 75-80 K. The values of the resistances $R_n$ were in the range of 0.2-0.5 Ohm.

The fabricated YBa$_2$Cu$_3$O$_{x-}$ bicrystal junctions were integrated with a log-periodical sinuous YBa$_2$Cu$_3$O$_{x-}$ antenna and a photo of one of these junctions is shown in figure 3. The 2μm-wide
YBa$_2$Cu$_3$O$_{7-x}$ bridge, crossing a MgO bicrystal boundary, is situated in the apex of the antenna. The MgO bicrystal boundary is situated horizontally in figure 3 and it is not visible due to the absence of polarization contrast in cubic MgO crystals.

The antenna has 25 legs on each side of the antenna. Its log-periodical geometry is defined by the constant ratio between the radii $R_n$ of nearest legs, namely, $R_{n+1}/R_n = 1.25$ ($n = 1, 2, 3 \ldots$), with maximum and minimum radii $R_{25} = 1000 \mu$m and $R_1 = 5 \mu$m. The substrate with the Josephson junction and the antenna was mounted on a sample holder, where a Si hyperhemispherical lens was also attached for focusing external radiation on the antenna. The sample holder was mounted on the coldfinger of the cryocooler.

**Figure 3.** Photo of a YBa$_2$Cu$_3$O$_{7-x}$ bicrystal junction with an integrated log-periodic sinuous antenna in transmitted light (left) and a sample holder with a focusing Si lens (right).

To bias the Josephson junction, we used a voltage-bias scheme with an active feedback, which was suggested to us by N. Ukhansky and is similar to one, previously presented in [23]. The voltage bias was chosen because it is more natural for spectroscopic purposes, than a current bias, since the measured frequency is associated with the voltage across the Josephson junction by Josephson relation $f = 2eV/h$. A simplified schematic of developed electronics is presented in figure 4. An asymmetric voltage $V_{in}$, which is proportional to the voltage $V$ across the junction, is converted into a symmetric one with a help of two buffers (+1 and -1) and, after a resistive divider, applied to the inverting inputs of operational amplifiers A1 and A2, serving as a reference level for the rest of the scheme. The voltage across the Josephson junction (JJ) is amplified by a cryogenic low-noise amplifier LNA, which was attached to the same sample holder as the junction. We used an amplifier LNA1657 with an input voltage noise of 0.17 nV/Hz$^{1/2}$ at 77 K [24]. The output voltage from the LNA was connected to the noninverting inputs of A1 and A2, thus closing the feedback loop. A differential instrumental amplifier A3, connected to the outputs of A1 and A2, gives the output voltage $V_{out}$, proportional to the junction current $I$.

The voltage bias electronics integrated in the demonstrator with SL200 cryocooler had a frequency bandwidth of 6 MHz and could deliver a maximum current of 25 mA through the junction. A similar electronics was mounted into the demonstrator with the LSF9589 cryocooler, but, to be applicable to the junctions with low values of normal-state resistances, the frequency bandwidth was reduced to 1 MHz and maximum current was increased to 60 mA.

To reduce the impact of interference noise on the Josephson junction, the electronics was powered by Li-ion rechargeable batteries, a differential scheme was used for all parts of electronics and all inputs and outputs were filtered by feedthrough capacitors. Use of cryogenic low noise amplifier allows us to reduce the scanning time at least up to 30 times, compared with the conventional low-noise room-temperature amplifiers, keeping the same signal-to-noise ratio.
3.3. Characterization of Hilbert spectrometer

An operation of the developed Hilbert spectrometers was carefully studied by characterization of low-frequency noise spectra and an instrumental function. Measured noise power spectra showed $1/f$ dependences of junction noise, which could spread to the frequencies up to a few hundreds kilohertz at dc voltages above 1 mV before it reaches the noise level of the preamplifier. Thus, amplitude modulation of external radiation with the frequencies of hundreds of kilohertz is required to reach the limitation of signal/noise ratio imposed by the cryogenic preamplifier. In this work, PIN switches with a maximum repetition rate of around 100 kHz for the modulation of the external radiation sources were used during characterization of Hilbert spectrometers and measurements of reflectance from bottled liquids. In these circumstances, a level of total noise during measurements at voltages of around 1 mV might be above the level of preamplifier noise only by a factor of 2-3.

An $I(V)$-curve of the [001]-tilt YBa$_2$Cu$_3$O$_{7-x}$ bicrystal junction, kept at 75 K in a Stirling cooler, and the response $\Delta I(V)$ of this junction to monochromatic radiation with a frequency $f$ of 254.7 GHz are shown in figure 5a. The response was measured at the modulation frequency of 50 kHz with the help of a lock-in amplifier. Time constants of 1 ms and lower were used during the spectral measurements, so that total measurement time could be reduced to a few seconds or even below one second.

The $I(V)$-curve is close to a hyperbolic form, which follows from RSJ model [17], when a critical current $I_c = 1.33$ mA and a normal-state resistance $R_n = 0.20$ Ohm are taken into account. The response $\Delta I(V)$ only shows one odd-symmetric resonance at the voltage $V = 0.527$ mV, which fits very well with the value of $hf/2e = 254.7$ GHz / 483.59 GHz/mV = 0.5267 mV. Actually, this procedure of measurements of the response to monochromatic radiation was used to calibrate the voltage scale of any Hilbert spectrometer.

Within an accuracy better than 1%, there are no subharmonic odd-symmetric resonances at $V_m = (hf/2e) \cdot (1/m)$, where $m = 2, 3, \ldots$, or harmonic resonances at $V_k = k \cdot (hf/2e)$, where $k = 2, 3, \ldots$, in the response $\Delta R(V)$ of this junction to monochromatic radiation. The first circumstance demonstrates a pure sin$\phi$-like contribution of Josephson current and absence of any parasitic shunting of the junction. The second circumstance shows that the power level of the external signal is inside the power dynamic range of the square-law Josephson detector.

Starting from the data presented in figure 5a, the spectrum of external monochromatic radiation was recovered using equation (1). The results of the calculation are presented in figure 5b. According to the measurement procedure, the spectrum in figure 5b is the instrumental function of the Hilbert spectrometer, because we applied a monochromatic signal to the spectrometer. From the point of view of junction physics, the spectrum in figure 5b is the spectrum of the main harmonic of Josephson oscillations at the voltage $V = 0.527$ mV. The peak value of the spectrum is situated at 254.7 GHz, which corresponds to the frequency of monochromatic source. The width of the line at 254.7 GHz is
equal to \((0.80 \pm 0.05)\) GHz, which is close to the intrinsic Josephson linewidth of 0.75 GHz, calculated for spectral broadening of Josephson oscillation by thermal fluctuations [17] at 75 K.

Due to a narrow, single-valued instrumental function, the developed Hilbert spectrometers give us a possibility to use them in the case of more complicated spectra, like polychromatic and continuous spectra.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure5.png}
\caption{The \(I(V)\)-curve of a YBa\(_2\)Cu\(_3\)O\(_{7-x}\) bicrystal junction at 75 K and its current response \(\Delta I(V)\) to monochromatic radiation with the frequency \(f = 255\) GHz (a). Spectrum of external radiation recovered from data in figure 5a by using equation (1) (b).}
\end{figure}

4. Polychromatic radiation source

One of the main problems in development of the demonstrator of a liquid identifier was a broadband source covering the dispersion range of the liquids under concern. In this paper we present our attempts to synthesize a required radiation source from the set of monochromatic and polychromatic sources available on the market. We have tested several sources at the frequency range from 5 GHz to 500 GHz, using our developed Hilbert spectrometers with high-quality instrumental functions like one, shown in figure 5b. It was found after tests, that most radiation sources, in addition to the main specified output frequency, also can deliver harmonics of the main frequency or harmonics of the pump frequencies in the case of multipliers.

With a total scanning time of a few seconds for our Hilbert spectrometers, radiation sources could be characterized very fast and in more details in the range, where conventional spectrum analyzers do not operate. We were able to test the operation of complicated multistage frequency multipliers, which start with the microwave frequencies \(f_0\), and multiply them by active stages \(\times 2\) and then \(\times 3\) to get the
frequencies at the W-band, which are in turn serve as pump frequencies for passive multipliers ×3 or ×5 to reach output frequencies of a few hundred gigahertz.

The results of the characterization of one of the W-band frequency multipliers with a nominal multiplication factor ×6 [25] are presented in figure 6. A frequency synthesized sweeper HP8630A was used to pump the multiplier and its frequencies were marked in figure 6 as input frequencies. A 100% amplitude modulation of microwave radiation from HP8630A was done by an external PIN switch at the frequency of 50 kHz. The spectra of output radiation of this multiplier were measured by the Hilbert spectrometer for each input frequency in the range from 9 to 21.5 GHz with the step of 0.05 GHz. Measurement time for each spectra was around 5 seconds for a lock-in time constant \( \tau \) of 1 ms. Measurements with \( \tau = 10 \mu s \) and total measurement times as low as 0.2 s were also demonstrated with reasonable signal/noise ratios and dynamic errors.

![Figure 6. Spectra \( S(\text{fout}, \text{fin}) \) of output radiation from a frequency multiplier measured by a Hilbert spectrometer.](image)

In figure 6 a selected set of measured spectra are presented in a waterfall sequence, which together gives a two-dimensional presentation of output spectra \( S(\text{fout}, \text{fin}) \) for the multiplier under study. As one can see from the output intensity distribution in figure 5, with an increase of the input frequency from 9 to 21 GHz the output radiation may be described as monochromatic with the frequency \( \text{fout} = 6 \times \text{fin} \) only at the range of input frequencies from 14 to 19 GHz. The output radiation might contain also the components with the multiplication factors \( n = 8, 10, 12 \), when the input frequency \( \text{fin} \) is between 9 and 14 GHz, and the components with \( n = 3, 4, 5 \), when \( \text{fin} \) is between 19 and 21 GHz. These additional frequency components are not desirable for using this multiplier as a monochromatic source in W-band, but might be useful in developing a polychromatic source for our liquid identifier. We used this multiplier as a pump source for passive multipliers to get a polychromatic source at the frequency range of several hundred gigahertzes up to 500 GHz. The results of Hilbert spectroscopy of these polychromatic sources will be published elsewhere [26].
5. Spectral reflectance from bottled liquids

A photo of one of the set-ups, used in the reflectance measurements of bottled liquids, is shown in figure 7. The Hilbert spectrometer with the cryocooler SL200 is placed on the left side. A radiation source made from a frequency multiplier is on the right side of figure 7. Polychromatic radiation from the multiplier was focused by an elliptical mirror on the bottle with the liquid, and the radiation, reflected from the bottle, was focused on the Josephson detector with the help of the second elliptical mirror. The output of the multiplier, depending on the frequency of the microwave pump, consists of several lines of high-order harmonics of the microwave pump oscillator. The voltage dependences of the detector response $I(V)$ were recorded by a lock-in amplifier and processed into the spectrum by equation (1). Two time constants $\tau$ of 1 ms and 10 $\mu$s were used, thus giving total measurement time of 5 seconds and 0.05 seconds, correspondingly.

![Figure 7. Simplified experimental set-up for measurements of reflectance from bottled liquids.](image)

Various combinations of conventional multipliers and their microwave pump oscillators were used to synthesize a radiation source which covers the dispersion range of liquids under concern. The input signal from a microwave oscillator, which excites a multiplier, was divided by a directional coupler into a main part, which was used to pump a multiplier, and to a low-level part, which, by a cable, was connected to a metal pin in the output horn of the multiplier (see figure 7, right part). Thus, we could get a polychromatic output signal, consisting of the microwave pump frequency $f$ and the frequency with a nominal frequency of $n \times f$. By this technique and using a combination of two multipliers, we succeeded in developing a source, which has 5 spectral lines at frequencies 15.3, 30.6, 91.8, 282 and 376 GHz in the output spectrum.

Various types of containers for liquids, like glass and plastic bottles, were tested in the experiments. A surface shape and material of the bottles could have some impact on the measured spectra. So, we made a special container with a flat Teflon window with a uniform thickness of 2 mm. Liquids under study were filled in the same container and the effects of uncertainties related with bottles were reduced. The errors of reflection measurements of bottled liquids, induced by various materials of bottles, and techniques to reduce these errors will be studied later.

The calibration of the reflectance in the set-up was carried out with a metal plate, installed inside the Teflon container just behind the wall. A corresponding polychromatic spectrum is shown in figure 8 by light grey color. The spectral resolution was 6.8 GHz at a frequency of 15.3 GHz, because of increase of differential resistance at low voltages, and 0.7 GHz at a frequency of 282 GHz. The values of spectral resolution were in an agreement with the prediction of the RSJ model, if a linewidth broadening by thermal fluctuations was taken into account [17].
When the metal plate in the container was replaced by water, the intensities of all five peaks in the spectrum went down. One can see in figure 8 that the 282 GHz-component decreased by a factor of 10 times compared to its initial value, while the 15.3 GHz-, 30.6 GHz- and 91.8 GHz- components were decreased only by a factor of 1.4 - 2. The 376 GHz-component was completely suppressed after reflection from the water because of its initially low amplitude. When the container was filled with acetone, methanol, ethanol or propanol, the modification of reflection spectrum was even more pronounced as it is shown in figure 8.

The pronounced decrease in high-frequency components of the reflection spectra of liquids compared to the low-frequency components is due to the decrease of the dielectric function at the frequencies above the main dispersion range for a particular liquid and is specific for every liquid. The measured spectra in figure 8 are in only in a qualitative agreement with the reflection spectra, calculated in Debye approximation and for normal incidence of electromagnetic radiation [9] (see figure 1). Water is known to possess a high value of static dielectric constant $\varepsilon_0 \approx 80$ and relaxation time $\tau = 8.3$ ps, i.e. the reflectance should be high in the frequency range up to around 100 GHz and much lower at the higher frequencies. This behaviour is consistent with spectrum for water in figure 8. Ethanol has $\varepsilon_0 \approx 20$ and $\tau = 163$ ps and, thus, it has low values of reflectance at the spectral range above 10 GHz. The static value of $\varepsilon_0 \approx 20$ for acetone is close to that of ethanol, but relaxation time $\tau = 3.3$ ps for acetone is even lower than that of water. So, the reflection spectra of acetone should be between those of water and ethanol, as one see from figure 8.

A set of reflection coefficients at four frequencies was acquired for each of five liquids. According to these sets, the liquids under study could be easily identified in our experiments. To extend these experiments from a simple liquid identification to a complete recovery of the dielectric functions $\varepsilon(f)$ of liquids, we should develop a transformation algorithm of our reflection spectra into $\varepsilon(f)$, which will take into account angle distributions of incident and reflected radiation.

Special care was taken to carry out our measurements within the power dynamic range of the Josephson detector. According to our estimates, the power dynamic range of the Josephson junction with a normal-state resistance of 0.2 Ω at a temperature of 80.6 K is in the range of 54-59 dB (for the postdetection bandwidth of 1 Hz) at frequencies from 15.3 GHz to 376 GHz. Taking into account the voltage noise $V_n = 0.17$ nV/Hz$^{1/2}$ of cryogenic amplifier, values of power dynamic range of around 40 dB and 30 dB were obtained for time constants $\tau = 1$ ms and 10μs, correspondingly. Therefore, our measurements were indeed carried out within the power dynamic range of the Josephson detector. One can see in figure 8, that this conclusion is also confirmed by the absence of responses at the harmonic frequencies which might arise at too high power of incident radiation.
Our first experiments showed that with simple measurements at four frequencies we are able to perform fast and reliable identification of various widespread liquids, such as water, methanol, ethanol, propanol and acetone, placed in a plastic container. Our experiments show that spectral measurements, covering the dispersion range of liquids, are more reliable for liquid identification than conventional approaches involving measurements at single low frequency only. The signal/noise ratio in our reflection measurements was higher than $2 \times 10^2$, which is sufficient to resolve the reflectance difference of a few percent between water and hydrogen peroxide.

Work is in progress to optimize the parameters of high-$T_c$ Josephson detector, improve the dynamics of data acquisition, and enhance the number of spectral lines and spectral range of the composite radiation source. With these developments, we can improve the dynamics and signal-to-noise ratio of our demonstration setup for identification of bottled liquids and make a significant step to a practical device.

6. Conclusions
We have presented a concept and the results of the development of liquid identifier, based on Hilbert spectroscopy and high-$T_c$ Josephson junctions. Two compact experimental setups, consisting of Hilbert spectrometers, integrated into Stirling coolers, have been developed. Polychromatic radiation sources were synthesized and characterized by the Hilbert spectrometers at the frequency range from 10 to 500 GHz. The reflection spectra of five bottled liquids have been measured and the experimental results showed significant modifications of reflection spectra, specific for each liquid under study. Total scanning time at sub second range has been demonstrated for Hilbert spectroscopy in these spectral measurements at a frequency range up to 400 GHz.

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