

Superconductivity Centennial Conference

## Josephson spectrometer with waveguide coupling for liquid identification

M. Lyatti<sup>a,b</sup>, a\*, U. Poppe<sup>b</sup>, Y. Divin<sup>b</sup>

<sup>a</sup> Kotel'nikov Institute of Radio Engineering and Electronics of RAS, 125009 Moscow, Russia

<sup>b</sup> PGI, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany

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### Abstract

Fast and reliable liquid identification is possible, in principle, by Josephson spectroscopy at subterahertz and terahertz ranges, but high speed of measurements, extended frequency range and high accuracy of intensity measurements are required. Quasioptical radiation coupling used in our previous demonstrators of the identifier can not be used at low frequencies where diffraction losses increase drastically. In this paper, we describe a new spectrometer based on a frequency-selective high- $T_c$  Josephson detector with dielectric waveguide coupling and consider its frequency scanning speed limit at a given accuracy of power measurement. According to our estimations, frequency scanning speed up to 1.3 THz/sec can be achieved if spectral resolution and power measurement error are 3 GHz and 0.1%, respectively. We have developed new compact radiation coupling system based on dielectric waveguides, which extends low frequency limit of our spectrometer down to 1.75 GHz. Small spread of angles of incidence of radiation and polarization control allow to recover the dielectric constants of the substance under test in a more simple way than in the case of quasioptical coupling. The results of first measurements with the new radiation coupling will be presented in our paper.

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Josephson junctions; terahertz spectroscopy; identification of liquids

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### 1. Introduction

Fast and reliable identification of liquids is a great challenge for security measures in airports and public places. Recently, we have presented a new identification method for bottled liquid based on

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M. Lyatti Corresponding author.

E-mail address: [matvey\\_1@mail.ru](mailto:matvey_1@mail.ru).

Josephson spectroscopy [1]. In our experiments, elliptical mirrors were used to focus radiation from a source to liquid, collect reflected radiation from liquid in a bottle and focused on a Josephson spectrometer. This quasioptical approach is quite simple and allowed us to demonstrate main advantages of our technique. However, the radiation coupling unit of this kind suffers from large losses at low frequencies, where diffraction of radiation on mirrors, beam splitters and polarizers becomes essential. Also, additional reflection from air-bottle interface reduces an accuracy of liquid identification when bottles with thin walls are used. These two problems might be solved when radiation coupling unit is fabricated from a dielectric waveguide. As the result, it might allow us to use all potential advantages of Josephson spectroscopy, i.e. a unique combination of a broad frequency range, an extended power dynamic range and a high scanning speed [2].

Here, we present theoretical evaluation of the maximum frequency scanning speed at given measurement accuracy for a frequency-selective Josephson detector, a description of Josephson spectrometer for liquid identification with dielectric waveguides and results obtained by this spectrometer.

## 2. Optimization of scanning speed of frequency-selective Josephson detector

Our previous measurements showed that the difference between reflection spectra of safe and threat liquids can be as small as few percent like in case of pure water and water solution of  $H_2O_2$  [3]. Fast and reliable identification of such small differences in reflection spectra requires of high measurement accuracy. In the case of a frequency-selective detection by the Josephson detector dynamic errors should be taken into account together with other measurement errors.

Three time dependencies of an average voltage  $V(t)$  across a Josephson junction (JJ), an average current  $I(t)$  through JJ and a current response  $\Delta I(t)$  of JJ to an external radiation are measured in Josephson spectroscopy. Measurement channels for voltage, current and response have limited bandwidths and due to limited bandwidths they contribute dynamic errors to  $V(t)$ ,  $I(t)$  and  $\Delta I(t)$ .

The sharpest feature, odd-symmetric resonance, appears in the current response  $\Delta I(V)$  when a monochromatic signal is applied to the JJ. In the frame of resistively shunted junction model, current response of JJ on monochromatic radiation with frequency  $f_s$  is given by [4]

$$\Delta I = I_s^2 \frac{2e}{h} \frac{I_c^2 R_n^2}{8I_0 V} \left[ \frac{f_j - f_s}{(f_j - f_s)^2 + (\delta f / 2)^2} + \frac{f_j + f_s}{(f_j + f_s)^2 + (\delta f / 2)^2} \right], \quad (1)$$

where  $I_s$  is the radiation induced current,  $I_c$  is the critical current of JJ,  $R_n$  is the normal-state resistance of JJ,  $I_0$  is the direct current through JJ,  $V$  is the voltage across JJ,  $f_j$  is the voltage controlled frequency of internal Josephson oscillations,  $\delta f$  is the Josephson oscillations linewidth.

Let voltage across JJ increase linear with time  $V(t)=v \cdot t$ , where  $v$  is the speed of voltage scanning. Then applying direct Fourier transform to  $\Delta I(t)$  and subsequently applying inverse Fourier transform together with the filter function  $F(\omega)$  ( $F(\omega) = 1$  at the frequency interval  $(-\pi B_R; \pi B_R)$  and  $F(\omega)=0$  outside this interval) we can get the current response  $\Delta \tilde{I}(V)$ , distorted by a low-pass filter

$$\Delta \tilde{I}(V) = \Delta I(V) \left[ 1 - e^{-\pi B_R \delta V / v} \left( \cos \left( 2\pi B_R \frac{V_j - V_s}{v} \right) + \frac{\delta V}{2(V_j - V_s)} \sin \left( 2\pi B_R \frac{V_j - V_s}{v} \right) \right) \right], \quad (2)$$

where  $V_j = (h/2e)f_j$ ,  $V_s = (h/2e)f_s$ ,  $\delta V = (h/2e)\delta f$  and  $B_R$  is the frequency bandwidth of the response channel. The distorted current response at different voltage scanning speeds is shown in Fig. 1.

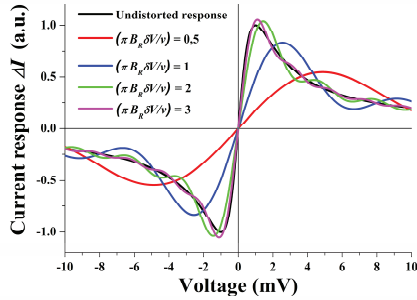


Fig. 1. Response function at different speeds of voltage scanning

Table 1. Estimations of the maximum frequency scanning speed of frequency-selective Josephson detector. Value of relative measurement error is equal to  $10^{-3}$

Spectral resolution (GHz)	Frequency bandwidth (kHz)	Scanning speed (THz/sec)
1	1	0.4
3	1	1.3
10	1	4.3
1	10	4.3
3	10	13
10	10	43

The relative error of the response amplitude measurement can be defined as  $|\Delta I_{max} - \tilde{\Delta I}_{max}| / \Delta I_{max}$ , where  $\Delta I_{max}$  and  $\tilde{\Delta I}_{max}$  are maxima of undistorted and distorted response functions, correspondingly. In our case small distortions are of interest. Then the relative error  $\eta$  of the response amplitude measurement can be given by

$$\eta = \left| \Delta I(V_s - \delta V) - \tilde{\Delta I}(V_s - \delta V) \right| / \Delta I(V_s - \delta V) \leq \sqrt{2} \cdot e^{-\pi B_R \frac{\delta V}{v}} \tag{3}$$

Thus the maximum speed of voltage scanning can be found from equation (3) as

$$v = \pi B_R \delta V / (0.5 \ln(2) - \ln(\eta)) \tag{4}$$

and the corresponding maximum speed of frequency scanning  $v_f$  is given by expression

$$v_f = \pi B_R \delta f / (0.5 \ln(2) - \ln(\eta)) \tag{5}$$

Using typical for our experiment values of the response channel bandwidth of 1 kHz, the relative error of the response measurement of  $10^{-3}$  and Josephson oscillations linewidth of 3 GHz, we can estimate the maximum allowable frequency scanning speed as 1.3 THz/sec. Other estimations of the frequency scanning speed are presented in Table 1.

### 3. Experimental details

To extend frequency bandwidth of our liquid identifier we have developed a new approach based on nonradiative dielectric (NRD) waveguides [5]. Advantages of this approach are the frequency bandwidth extended down to dc frequencies, the possibility to realize compact instrument and reduction of parasitic reflections. The waveguide approach also gives a possibility to use polychromatic radiation sources where higher harmonics propagate at some angle with respect to the main optical axis.

A photo of an experimental setup is presented in Fig. 2. The experimental setup consists of a set of radiation sources (shown in the right upper corner of Fig. 2), a radiation coupler (in the center of Fig. 2), NRD waveguides with a prism, a cell with a liquid and the Josephson detector (shown in the left upper corner of Fig. 2). The radiation of microwave sources is coupled to a central waveguide by the radiation coupler. Then the radiation is guided to the prism and after reflection from the liquid the radiation is directed by an other NRD waveguide to the Josephson detector. Waveguides and the prism were made of

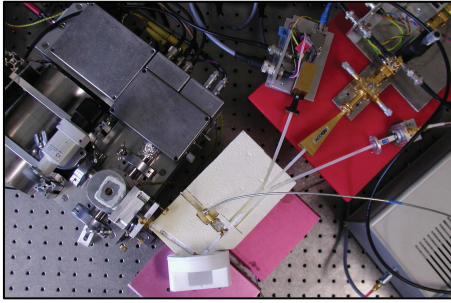


Fig. 2. Photo of experimental setup

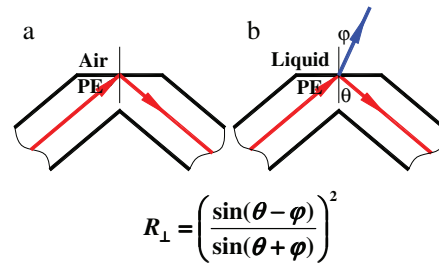


Fig. 3. Radiation propagation when nothing is attached to the prism (a) and when the cell with a liquid is attached to the prism (b).

high density polyethylene (PE) as one unit to avoid radiation losses. Waveguides had a rectangular cross section of 2x4mm. Upper and lower metal plates of waveguides were made of copper foil.

Waveguides and prism were made of PE because the refractive index of PE is close to the refractive index of PET which is widely used for the bottle fabrication. Thus the reflection from the PE-PET interface is reduced compared to the reflection from the air-PET interface. Additionally PE has low losses in the subTHz and THz frequency range and flexible PE waveguides can be easily shaped.

The angle of incidence of radiation on the surface of the prism was  $50^\circ$  in our setup. This angle is larger than angle of total internal reflection from the PE-air interface [6]. Thus radiation conducted to the prism was totally reflected to the Josephson detector when nothing is attached to the prism. The prism length allowed only one reflection as it is shown in Fig. 3a. If the cell with a liquid is attached to the prism surface then conditions of total internal reflection are broken as it is shown in Fig. 3b. As upper and lower metal plates were placed over the whole length of the central waveguide the radiation polarisation was perpendicular to the plane of incidence and Fresnel equations for s-polarized radiation can be used to recover the refractive index of the liquid [6]. At low frequencies when radiation wavelength is much larger than dimensions of the waveguide these assumptions are not longer valid. In this case field is concentrated between upper and lower metal plates even when a liquid with high dielectric constant is attached to the prism and the attenuation of the signal occurs due to losses in a liquid.

The set of radiation sources used in the experiment consisted of 3 high frequency sources: a multiplier by 3 with an input frequency of 24 GHz, a multiplier by 6 which with an input frequency of 15.8 GHz and a multiplier by 3, which was pumped by a Gunn oscillator with a frequency of 94 GHz, and one low frequency source. The synthesizer HP83630A was used as a low source frequency source.

The radiation of different sources was combined into the central waveguide by the radiation coupler. To build this coupler we used the method described in the work [7]. Waveguides were fixed in a base plate with grooves. The base plate was made of commercially available extruded polystyrene rigid foam URSA XPS with a very low dielectric constant. Low frequencies were injected into the waveguide by a SMA plug which was connected to the upper and lower plates of NRD via a microstrip waveguide.

As a radiation detector the Josephson detector based on a [001]-tilt  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  grain-boundary junction was used. JJ was cooled down to 77.3 K by the Stirling cryocooler LSF9589 (Thales Cryogenics B.V.). The operating temperature of 77.3 K was maintained with an accuracy of 10 mK by the cryocooler controller HPCDE 2465 (Thales Cryogenics B.V.). During measurements this detector was operated in two regimes: a broadband regime and a frequency-selective regime. Details on these regimes were published elsewhere [8]. In the broadband regime monochromatic signals with frequencies in the range of 1.75–16.88 GHz were applied consecutively and the response on these signals was measured at constant voltage bias close to zero. During low frequency measurements all high frequency sources were switched off. After these measurements the low-frequency source was switched off, high-frequency sources were

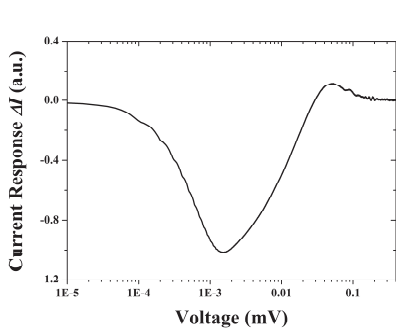


Fig. 4. Broadband response of Josephson detector

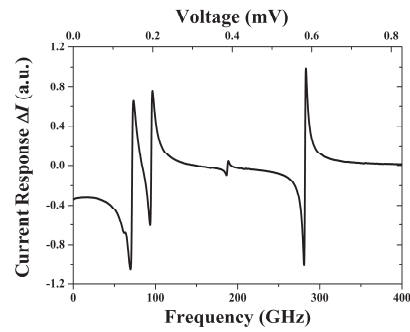


Fig. 5. Frequency-selective response of Josephson detector

switched on and the frequency-selective response was measured. All responses were measured by a lock-in amplifier at a modulation frequency of 50 kHz.

#### 4. Results and discussion

Several pure liquids such as water, acetone, methanol, ethanol and propanol were used to test the new design of the liquid identifier. During measurements the liquid under test was placed in the cell with thin PE window. The thin flexible window provided good contact between liquid and PE prism. In our tests water was used as a reference liquid.

The [001]-tilt  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  grain-boundary junction used in the experiment had a normal-state resistance  $R_n$  of 0.3 Ohm and an  $I_c R_n$ -product of 0.17 mV at 77.3 K.

During low frequency measurements the output power of the frequency synthesizer HP83630A was constant at the different frequency points. The radiation power coupled to the NRD waveguide was estimated to be less than 5  $\mu\text{W}$ . An adjustment of the response values for water was made by a proper choice of frequency values. Six low frequency values were used: 1.75 GHz, 4.2 GHz, 5 GHz, 8.06 GHz, 13.1 GHz and 16.88 GHz. An example of the broadband response of the Josephson detector is shown in Fig. 4. The results of these measurements are presented in Table 2.

In Fig. 5 one can see the current response function of Josephson detector when the reflection of high frequency polychromatic radiation from the cell with water is measured. There are four frequency-selective resonances which correspond to frequencies of 72 GHz, 95 GHz, 188 GHz and 282 GHz on the response function. Intensities of three lines with frequencies of 72 GHz, 95 GHz and 282 GHz were adjusted to get nearly the same resonance amplitudes when the reflection from water was measured. A line with frequency of 188 GHz which is a second harmonic of the multiplier with input frequency of 94 GHz had low intensity and we did not use it in our measurements. Results of high frequency measurements are also presented in Table 2.

To compare measured values with literature data we have calculated reflection coefficients for water and ethanol. Using values of the static dielectric constant, infinite frequency permittivity and relaxation times from [9] we got reflection coefficients for water and ethanol. After normalization on water reflection coefficients, ethanol reflection coefficients were 0.22, 0.24 and 0.38 for frequencies of 72 GHz, 95 GHz and 282 GHz, correspondingly. These values are close to our results for ethanol.

Low frequency data also demonstrated at least qualitative agreement with literature data. According to the data from the work [9], at a frequency of 1.75 GHz the imaginary part of dielectric constant  $\epsilon_2$  of water is larger than  $\epsilon_2$  of acetone but smaller than  $\epsilon_2$  of methanol and ethanol. At frequency of 4.2 GHz  $\epsilon_2$  of water is larger than  $\epsilon_2$  of acetone, methanol and ethanol. This correlates with our data when losses for water at frequency of 1.75 GHz are larger than losses for acetone but less than losses for methanol and

Table 2. Identifier responses for pure liquids

Frequency(GHz)	Water	Acetone	Methanol	Ethanol	Propanol
1.75	1	2.43	0.86	0.74	0.95
4.2	1	1.31	1.14	1.41	1.64
5	1	1.17	1.17	1.37	1.55
8.06	1	1.35	2,00	2.62	4,00
13.1	1	0.95	0.93	1.20	1.49
16.88	1	0.55	0.14	0.02	0.08
72	1	0.77	0.36	0.17	0.07
95	1	0.83	0.47	0.25	0.14
282	1	0.88	0.61	0.42	0.31

ethanol. At frequency of 4.2 GHz losses for water are larger than losses for acetone, methanol and ethanol.

## 5. Conclusions

New design of Josephson spectrometer with waveguide coupling for liquid identification was developed. Extended frequency bandwidth from 1.75 GHz to 282 GHz has been demonstrated. First measurements with pure liquids have been made. Due to new design the refraction index of liquid under the test can be recovered by Fresnel equations when radiation polarization is perpendicular to the plane of incidence. Also, we have presented theoretical estimations of maximum frequency scanning speed of the frequency-selective Josephson detector.

## Acknowledgements

This work is supported by the joint project HRJRG-207 of Helmholtz Association of German Research Centers and Russian Fund for Basic Research (project 11-02-91321-SIG\_a).

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