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Testing of Josephson Spectrometer with Waveguide Coupling

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Abstract. One of the challenges in public security is the quick and reliable identification of threat liquids in bottles, when vapour analysis is not possible. Recently, we demonstrated that it is possible to rapidly identify liquids by EM measurements of their dielectric functions in the sub-THz range with a high- T_c Josephson spectrometer. Following this approach, we have developed a Josephson spectrometer with a new radiation coupling system, based on dielectric waveguides. In this paper, we present the results of spectroscopic measurements on liquid samples of various purities including 30% $\text{H}_2\text{O}_2/\text{H}_2\text{O}$, performed using our Josephson spectrometer with waveguide coupling. Also, the signal and noise characteristics of a classical Josephson detector used in our liquid identifier were numerically simulated and the power dynamic range was estimated for a wide spread of junction parameters.

1. Introduction

Among various discussed ways, the techniques using electromagnetic radiation for liquid explosive detection are considered as one of the most promising [1]. It has been shown that the fast identification of harmless and threat liquids, including 30% $\text{H}_2\text{O}_2/\text{H}_2\text{O}$ solution, can be performed with a Josephson spectrometer in the sub-THz frequency range [2]. Recently, we demonstrated a new type of liquid identifier based on the Josephson spectrometer with waveguide coupling [3]. Both classical and frequency-selective modes of a Josephson detector were used. The frequency bandwidth of the liquid identifier was extended to include lower frequencies down to 1 GHz. Due to two different detection techniques at low and high frequencies, the response of the liquid identifier with waveguide coupling was very specific, which was favourable for reliable identification. In this paper, we present a theoretical evaluation of the power dynamic range of the classical Josephson detector and results on the identification of liquids with various purities by the liquid identifier with waveguide coupling.

2. Power dynamic range of classical Josephson detector

At low frequencies, a classical mode of the Josephson detector is used in our liquid identifier. In this mode, a nonlinearity of the dc IV -curve of a Josephson junction is used to detect radiation with a frequency f , which is low enough compared with the characteristic Josephson frequency $f_c = (2e/h) \cdot I_c R_n$, where I_c is the critical current and R_n is the normal-state resistance. In the first approximation, a response of the classical Josephson detector is proportional to the second derivative of the IV -curve of the Josephson junction [4].

In contrast to the well-studied power dynamic range of the frequency-selective Josephson detector



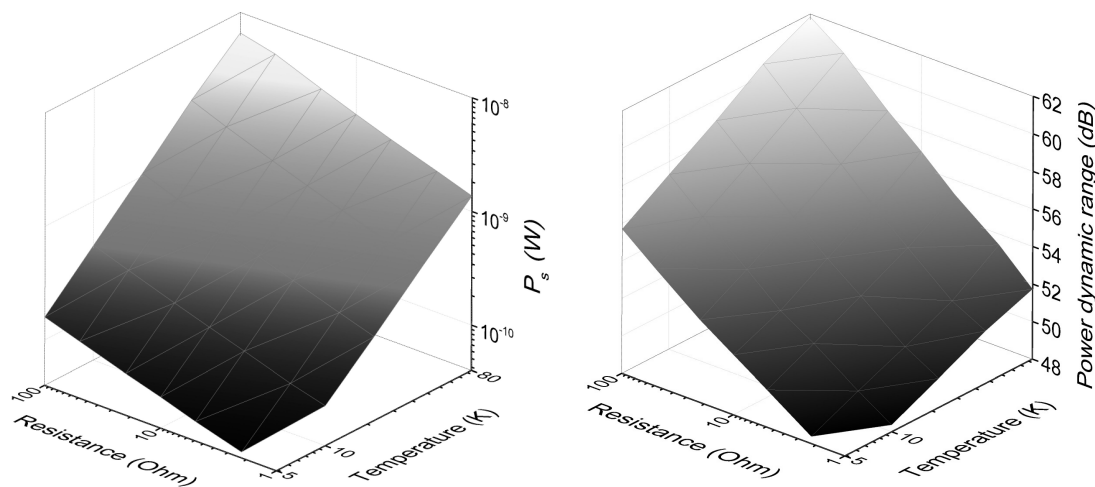


Figure 1. High-power limit P_s of the power dynamic range (left) and the power dynamic range (right) of the classical Josephson detector with $I_c R_n = 1$ mV vs. normal-state resistance and temperature.

[5]-[7], there is a lack of data on the power dynamic range of the classical Josephson detector. Numerical simulation of signal and noise characteristics of the classical Josephson detector based on the solution of the Fokker-Planck equation was carried out for the resistively shunted junction model with thermal fluctuations. The simulations were carried out over the range of normal-state resistances of the Josephson junction $R_n = 1 - 100$ ohm, critical currents $I_c = 0.01 - 1$ mA, and temperatures $T = 5 - 80$ K. The frequency f of incident radiation was set at $0.05f_c$.

The power dynamic range D of the detector is by definition $D = P_s/NEP$, where P_s is the high-power limit of the power dynamic range, and NEP is the noise-equivalent power of the detector. The high-power limit value P_s was taken as the level of the input power P , at which the detector responsivity $R = \Delta V/P$ decreases by a factor of two. The P_s -value was determined from the numerically simulated dependence of the classical response ΔV of a current-biased junction on input radiation. The ΔV -values were taken at the bias, corresponding to the response maximum at a low power of incident radiation. An example of dependence of P_s of the Josephson detector with $I_c R_n = 1$ mV on the normal-state resistance and temperature is presented in figure 1 (left). Analysis of the numerical simulation data revealed that the high-power limit of the power dynamic range of the classical Josephson detector can be described by equation $P_s[\text{watt}] = 4.07 \cdot 10^{-10} R_n[\text{ohm}] \cdot I_c^{2/3}[\text{A}] \cdot T^{4/3}[\text{K}]$ with 3% accuracy.

The values of NEP were numerically simulated at the same points as the values of P_s . Finally, the power dynamic range of the classical Josephson detector was obtained from the P_s and NEP values. An example of the dependence of the power dynamic range of the classical broadband Josephson detector on normal-state resistance and temperature is shown in figure 1 (right). It is clear from the numerical simulation that the power dynamic range of the classical Josephson detector can exceed 60 dB and both the normal-state resistance R_n and the $I_c R_n$ -product of the Josephson junction should be increased to obtain an extended power dynamic range.

3. Experimental setup

A photograph of the liquid identifier with waveguide coupling of radiation is shown in figure 2. A description of the experimental setup can be found in [3]. The liquid to be tested was poured into a cell with a thin high-density polyethylene (PE) window. The prism (see figure 2) and the cell window were made of the same material to eliminate any reflection from the cell window. At low frequencies, the radiation was coupled to the liquid by an evanescent field at the waveguide edge. At high frequencies, the radiation was attenuated by reflection from a PE-liquid interface. To reduce possible errors due to the procedure of inserting and removing the cell, the liquids were changed without moving the cell.

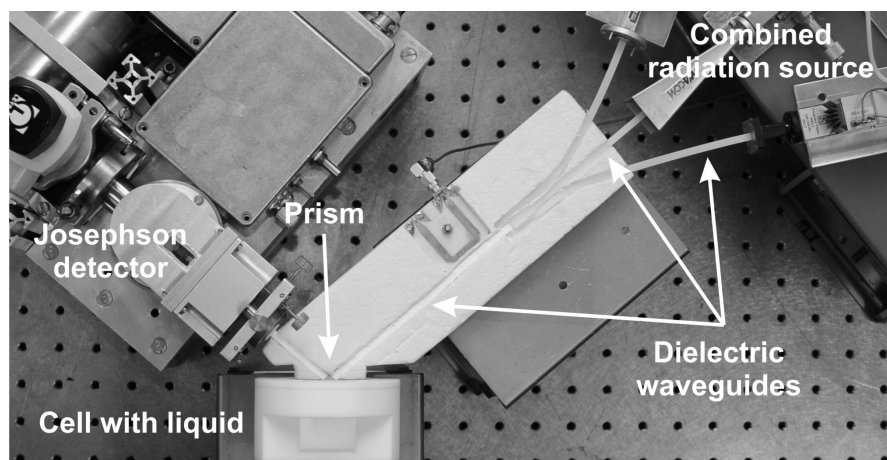


Figure 2. Photograph of liquid identifier with waveguide coupling

The combined radiation source consisted of 3 multipliers with output frequencies of 93 GHz (6×15.5 GHz), 186 GHz (12×15.5 GHz), and 282 GHz (3×94 GHz), and a frequency synthesizer HP83630A. The Josephson detector was based on a [001]-tilt $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ bicrystal junction with the normal-state resistance of 1.9 ohm and $I_c R_n$ -product of 0.23 mV at 69 K. The junction was cooled by a Stirling cryocooler (LSF9589, Thales Cryogenics B.V.). The operating temperature was maintained with an accuracy of 10 mK by a cryocooler controller (HPCDE 2465, Thales Cryogenics B.V.)

Both classical and frequency-selective modes of the Josephson detector were used to provide an extended frequency range. The classical mode was used for low-frequency measurements and the frequency-selective mode was used for high-frequency measurements. During low-frequency measurements, the output frequency of the frequency synthesizer was scanned in 1 MHz steps close to the resonance frequencies of the PE waveguide and the response of the Josephson detector was measured at each frequency. During high-frequency measurements, all multipliers were switched on simultaneously and the frequency-selective response of the Josephson detector was recorded. The line intensities of polychromatic radiation were then determined from the recorded frequency-selective response. All responses were measured by a lock-in amplifier at a modulation frequency of 100 kHz.

4. Identification of liquids

The liquid identifier was tested using different liquids of various purities including distilled deionized water (18.2 Mohm·cm), distilled water, tap water, acetone, methanol, ethanol, propanol, 30% $\text{H}_2\text{O}_2/\text{H}_2\text{O}$ suprapur®, and stabilized 30% $\text{H}_2\text{O}_2/\text{H}_2\text{O}$. The distilled deionized water was used as a reference liquid.

At low frequencies (< 20 GHz), the PE waveguide with metal plates above and below can be considered as a resonator. Multiple resonances with quality factors up to 400 were observed due to standing waves in the waveguide. Resonance frequencies and quality factors of the resonances were changed when the cell with liquid was attached to the prism. The response values at frequencies of 0.95, 1.7, 3.4, 9.5, 18.7 GHz were taken at the maxima of the resonances. Results of low-frequency measurements are presented in figure 3. Different measurement frequencies are colour-coded. The reference level of the responses for deionized water is shown by a dashed line.

The experimental results at low frequencies are correlated, as expected, with the imaginary part of the dielectric constants of the liquids. A higher response corresponds to lower losses. For example, the losses in ethanol are higher than the losses in water at about 1 GHz. The result is similar at a frequency of 2 GHz while losses are much lower at 20 GHz [8]. It can be seen that the response of a 30% solution of hydrogen peroxide in water is higher than the response of water of various purities at frequencies of 0.95 GHz and 1.7 GHz. These frequencies can be used as low-frequency markers for hydrogen peroxide.

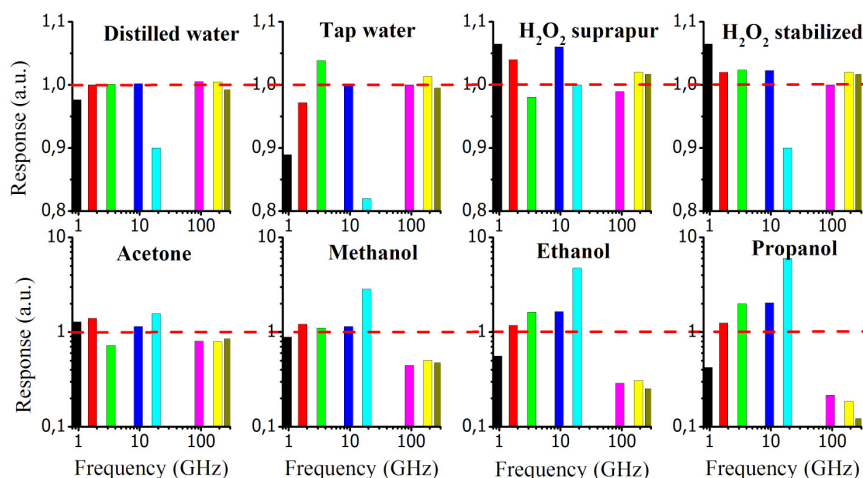


Figure 3. Responses of liquid identifier to different liquids of various purities. The 30% solutions of H_2O_2 in water are designated H_2O_2 .

At higher frequencies, the response is proportional to the reflectance of the liquid. The higher response corresponds to the higher reflection coefficient. The results of high-frequency measurements are also plotted in figure 3. There is a large difference between water-based liquids and the other liquids tested. No difference was found between water and both types of 30% $\text{H}_2\text{O}_2/\text{H}_2\text{O}$ at 93 GHz, and the response of 30% hydrogen peroxide was 2 % higher at 186 and 282 GHz. These results are consistent with our previous work in which quasioptical radiation coupling was used [2]. The difference between water of various purities and 30% hydrogen peroxide is not so pronounced at high frequencies as at low frequencies, but still large enough for a reliable distinction to be made.

Conclusions

The signal and noise characteristics of the classical Josephson detector were numerically simulated and the power dynamic range was estimated. Values of the power dynamic range above 60 dB are expected for high-resistance Josephson junctions.

A liquid identifier with waveguide coupling was tested using liquids of various purities. The ability to distinguish different liquids including water and diluted hydrogen peroxide of various purities was demonstrated both at low and high frequencies.

Acknowledgements

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