Terahertz Hilbert Spectroscopy

Using Nanoscale High-T_c Josephson Junctions

Introduction

The principle of Hilbert spectroscopy (HS) [1] is based on the ac Josephson effect in superconducting junctions. If a Josephson junction is irradiated, the electrical response *H(V)* of a Josephson junction is proportional to the Hilbert transform of the spectrum $S(f)$of incident radiation. Applying an inverse Hilbert transformation to the measured response *H(V),* the spectrum $S(f)$ might be recovered as follows:

$$S_{I_s^2}(f) = \left(\frac{1}{\pi}\right) \cdot P \int_{-\infty}^{\infty} \frac{H(f_j) \cdot df_j}{f_j - f}$$

where $f_j = 2eV/h$. Hilbert-transform spectroscopy is similar to Fourier-transform spectroscopy (FS). The important distinction, however, is in that in HS a direct transformation of the spectrum into an electrical signal is achieved by nanoelectronic device, a Josephson junction, while in FS this procedure requires a bulk optical-mechanical device, an interferometer, together with a broadband detector.

The simplicity of HTS together with its broad bandwidth, high sensitivity and short time constant of Josephson junctions might even result in commercial success. The spectrum analyzers and spectrometers based on the conventional techniques are very expensive, if their operational frequencies are extended from their traditional ranges to the intermediate range of subterahertz aand terahertz frequencies (see Fig. 1). In the intermediate frequency range from tens of GHz to several THz there is definitely a niche for Hilbert-Transform Spectroscopy.

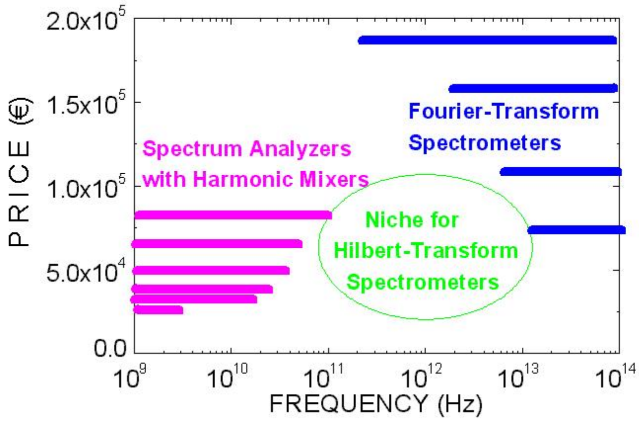

Fig. 1. Price vs. frequency range for conventional spectroscopic techniques and Hilbert spectroscopy.

Approach

We are developing the high-quality high-T_c Josephson junctions for application in the terahertz range. Starting from the fabrication of high-Tc thin films, we develop the high-T_c junctions. We study the corrrelation of nanostructure, revealed by Atomic Force Microscopy and High-Resolution Electron Microscopy, with the local electrical transport in these junctions and analysing the relation between the nanostructure and electrical terahertz response.

Results

High-T_c grain-boundary junctions

The main part in the Hilbert spectroscopy is a Josephson junction described by an idealized RSJ model. To operate in terahertz range, the junctions should have the characteristic voltages I_cR_n exceeding 1 mV. Due to the high value of the energy gap in high-T_c superconductors (20-60 meV), the high-T_c Josephson junctions with the I_cR_n-values exceeding 1 mV are better described by RSJ model than the low-T_c junctions. Among the different types of high-T_c junctions, the grain-boundary junctions are found to be best characterized by the RSJ model . The TEM image and micrograph of one of our high-T_c Josephson junctions developed for Hilbert spectroscopy is shown in Fig.2. The I_cR_n-values of RSJ-like junctions are up to 0.34 mV at 77K and up to 2 mV at 35 K.

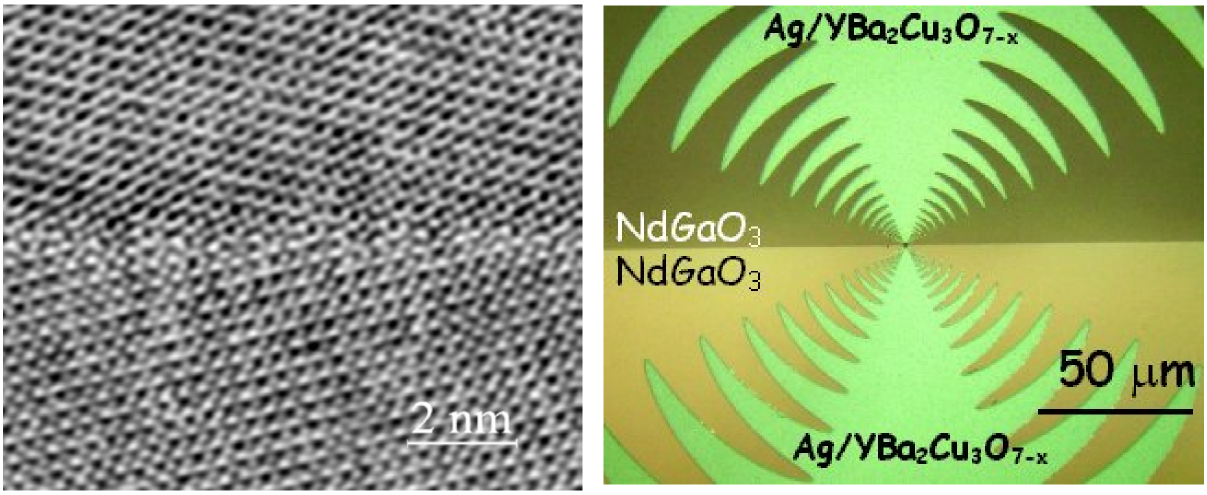

Fig. 2. TEM image of $YBa_2Cu_3O_{7-x}$ grain-boundary Josephson junction (left) and micrograph of the junction with integrated broadband antenna for Hilbert spectroscopy (right).

Spectral range of Hilbert spectroscopy

The spectral range of the Hilbert spectroscopy scales with the I_cR_n-values. For the I_cR_n-values of 1.5 mV it reaches the terahertz frequencies at low temperatures (Fig. 3). A high-frequency limit for the ac Josephson effect of 4.25 THz has been achieved and a spectral resolution δf/f of 10^{-3} has been demonstrated [2]. Presently, we are investigating the terahertz response of the junctions with I_cR_n-values up to 8 mV [3].

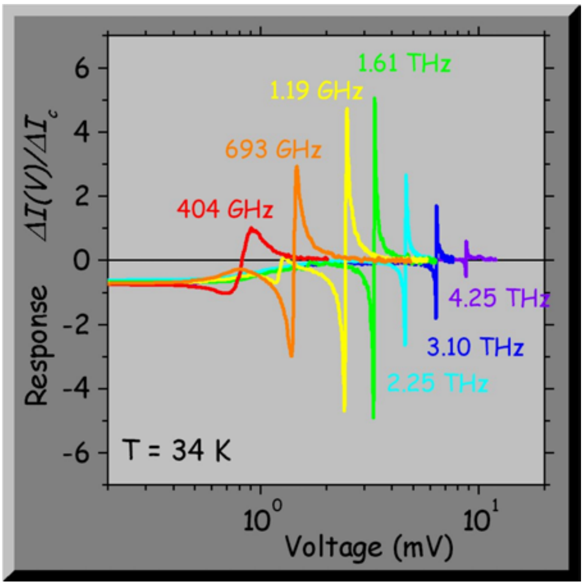

Fig. 3. Spectral range of the Hilbert spectroscopy using $YBa_2Cu_3O_{7-x}$ grain-boundary Josephson junction at 34 K.

Application

Several prototypes of Hilbert spectrometers have been developed and tested in collaboration with the Institute of Radio Engineering & Electronics of Russian Academy of Sciences (Moscow, Russia), Central Electronics Laboratory of Research Center Juelich and TESLA Test Facility at DESY (Hamburg). We have successfully measured the following emission spectra: Lorentz spectra of Josephson oscillations, high-harmonic contents of commercial millimeter-wave oscillators, polychromatic radiation from optically-pumped far-infrared gas lasers and spectra of coherent transition radiation from relativistic electron bunches at the TESLA Test facility at DESY (Hamburg) [2]. The interest to terahertz spectral analysis is increased in recent day due to the development of terahertz quantum cascade lasers and due to the development of subterahertz transistors for high-speed logic.

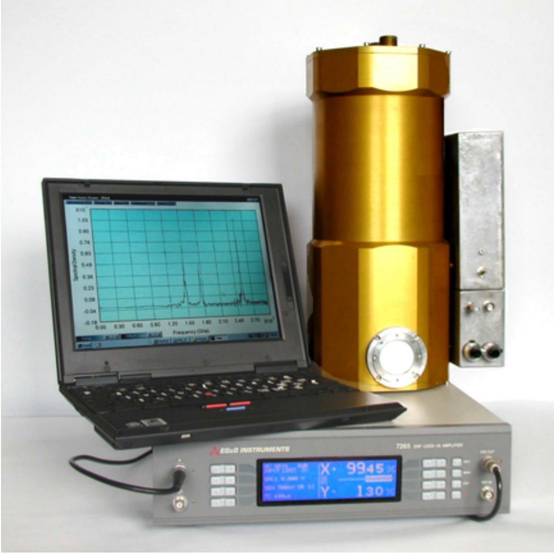

Fig. 4. Hilbert spectrometer, using an optical cryostat.

References

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[3] Y.Y.Divin, U. Poppe, C.L. Jia; P.M. Shadrin, K.Urban. *"Structural and electrical properties of* $YBa_2Cu_3O_{7-x}$ *[100]-tilt grain boundary Josephson junctions with large* I_cR_n*-product on* $SrTiO_3$ *bicrystals."* **Physica C**, vol. 372-376, pp. 115-118 ,2002.

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