Terahertz Applications of Hilbert-Transform Spectral Analysis

Yuriy Divin, Alexander Snezhko, Matvey Lyatti, Ulrich Poppe, Valery Pavlovskiy

(Invited paper)

***Abstract*— Bridging of the terahertz gap in the electromagnetic spectrum between the microwave and infrared ranges requires a variety of new technological developments from basic elements, like emitters and detectors, to complete systems, like spectrum analyzers and imagers. As an example of these developments, Hilbert-transform spectral analysis of terahertz radiation sources has been demonstrated. A spectrum analyzer based on a high-T_c square-law Josephson detector has been developed and characterized in the frequency range from 50 to 1800 GHz. Spectra of output terahertz radiation from optically-pumped lasers and frequency multipliers have been studied and their regimes were optimized for a single-frequency operation. Starting from the optimized multipliers, a polychromatic source has been synthesized and characterized with Hilbert-transform spectrum analyzer.**

***Index Terms*—Josephson junctions, high temperature superconductors, Hilbert transformation, terahertz technology, spectral analysis, frequency multipliers, optically-pumped lasers.**

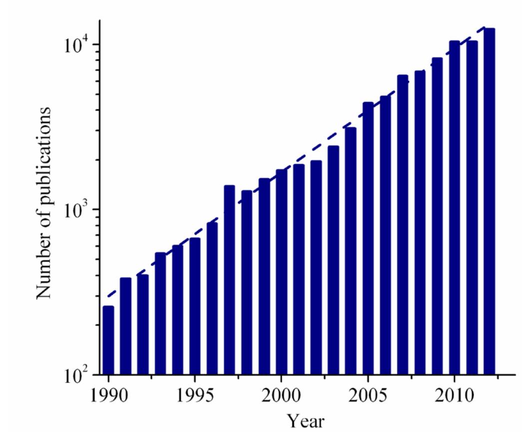


Fig.1. A number of publications per year with a term "terahertz" according to Google Scholar.

I. Introduction

NEW developments in the terahertz (THz) range demonstrate a permanent growth in a number of publications during last twenty years (see Fig. 1). Together with traditional THz applications in radioastronomy and condensed-matter physics, new applications are emerging in a variety of socially-important areas, like life sciences, homeland security, global environmental monitoring, and information and communication technologies [1]. The developments in the THz fields are characterized by optimistic market expectations. The global market for THz devices and systems is estimated to increase to around 500 million dollars by 2021 at a growth rate of 35% from 2016 to 2021 [2]. The main contribution to this increase is expected from new THz devices and systems for imaging, spectroscopy, communication and other sensors, while the impact of traditional fields, like radioastronomy, will decrease.

THz developments in electronics are mainly done within conventional technologies based on semiconductors. However, efficiency of these devices deteriorates, when their frequencies are extended into the THz range, and this trend is only partly compensated by parallel operation or powerful amplification of microwave or laser excitations.

Due to the coherent nature of the superconducting quantum state, superconducting electronic devices possess unprecedented functionalities and parameters compared with those of conventional semiconducting electronics [3]. For example, the ac Josephson effect in superconducting junctions [4] is the basis of dc voltage standards, detection and spectral analysis of electromagnetic radiation. Development of high-T_c Josephson junctions with THz characteristic frequencies paves the way to a variety of demanding applications in public security, life sciences and high-energy physics [5], [6].

Moreover, the operating temperatures of high-T_c devices are between 40 and 90 K [5]. In this temperature range, space-qualified, compact, essentially maintenance-free electrical coolers have recently been developed (see, e.g. [7]). These

Manuscript received December 30, 2013. This work was supported by the joint project HRJRG-207 of Helmholtz Association of German Research Centers and Russian Fund for Basic Research.

Y. Divin is with Forschungszentrum Jülich GmbH, 52428 Jülich, Germany (phone:+492461612394,fax:+492461616444; e-mail: Y.Divin@fz-juelich.de) and with the Kotel'nikov Institute of Radio Engineering and Electronics of Russian Academy of Sciences, Moscow, Russian Federation (e-mail: yyd@cplire.ru)

A. Snezhko and M. Lyatti are with Forschungszentrum Jülich GmbH, 52428 Jülich, Germany, on leave from the Kotel'nikov Institute of Radio Engineering and Electronics of Russian Academy of Sciences, Moscow, Russian Federation (snezhkoa@gmail.com, M.Laytti@fz-juelich.de)

U. Poppe is with Forschungszentrum Jülich GmbH, 52428 Jülich, Germany (U.Poppe@fz-juelich.de)

V. Pavlovskiy is with the Kotel'nikov Institute of Radio Engineering and Electronics of Russian Academy of Sciences, Moscow, Russian Federation (pvv@mail.cplire.ru).

technologies are in the process of changing the market for the application of high-T_c superconducting devices in many fields.

Recently, a THz Hilbert-transform spectrum analyzer has been developed based on dynamics and technology of high-T_c Josephson junctions [8]. An important and user-friendly aspect of this development is that an electrically-driven Stirling cooler was used to cool the junction for the temperature below the critical temperature of the superconducting material. Here, we present first THz applications of the developed Hilbert-transform spectrum analyzer with high-T_c Josephson junctions.

II. Theory

Theory of Hilbert-transform spectral analysis was published elsewhere [9]. Briefly, the ac Josephson effect gives rise to voltage-control Josephson oscillations with the frequency $f_j = 2eV_0/h$, where V_0 is the dc voltage across a Josephson junction. External monochromatic radiation with the frequency f induces the ac currents through the junction, the frequency of Josephson oscillations pulls to the frequency of external radiation and the dc voltage at the current bias I shifts from the voltage V_0 to the voltage $V = hf/2e$. The resulting response $\Delta V = V - V_0$ has an odd-symmetric form around the dc voltage V_0 and also it has a square-law dependence on the amplitude of the induced current I_1 at low intensities of the external signal. Thus, the Josephson junction operates as a quadratic detector with a frequency-selective resonance at $V \cong V_0$ in the dc response vs voltage characteristic. This effect in the Josephson oscillator is nothing new but a frequency-locking phenomenon in nonlinear dynamic systems with electrical noise.

To get the square-law response of the detector to electromagnetic radiation with arbitrary spectrum one can integrate the response curve with a frequency-selective resonance together with the spectrum of the induced currents $S(f)$. The resulting response ΔV vs. the dc voltage V was found to be proportional to the Hilbert-transform of the spectrum $S(f)$ [9]. Using the inverse Hilbert transform to the dc response of the Josephson detector one can recover the spectrum of the external radiation or the induced currents. Recovery is usually done according to standard relation between the Hilbert and Fourier transforms, i.e. with the double Fourier transform with an intermediate multiplication of the result of first Fourier transformation on the sign(f) function [10]. This recovery technique works very good [8] if the Josephson junction is described by the idealized resistively shunted junction (RSJ) model [4]. More complicated algorithms were used to recover the data in the case of the junctions with deviations from the RSJ model [11].

Hilbert-transform spectral analysis might demonstrate some advantages in the terahertz range where mostly the Fourier-transform spectral analysis is used based on the Michelson interferometer and broadband detectors operating at liquid-helium temperatures, like Si bolometer or InSb hot-electron bolometer. The large difference in Hilbert- and Fourier transform in relation to the monochromatic and broadband radiation gives hopes that the Hilbert-transform technique will be more useful in the case when the spectrum of external radiation consists of narrow lines with the intensive thermal background. Detailed discussion of the advantages of this kind will be presented elsewhere [12].

III. Spectrum Analyzer

The main part of the Hilbert-transform spectrum analyzer is a Josephson junction, which follows the RSJ model. We are able to fabricate this type of Josephson junctions based on high-temperature superconductor $YBa_2Cu_3O_{7-x}$ [13]. $YBa_2Cu_3O_{7-x}$ epitaxial thin films were deposited on bicrystal substrates ($NdGaO_3$ or MgO) using dc sputtering at high-oxygen pressure. In this type of the spectrum analyzer, $YBa_2Cu_3O_{7-x}$ bicrystal junctions with $R_n = (0.4 \div 0.6)$ Ohm and $I_cR_n(60\ K)$ of around 1 mV have been used.

A developed Hilbert-transform spectrum analyzer is described earlier [8]. A photo of the spectrum analyzer integrated on a compact, maintenance-free Stirling cooler SL200 (AIM Infrarot Module GmbH) is shown in Fig. 2. The cooler with high cooling power (3.5 W at 77 K) has been chosen. A compressor of the cooler was surrounded by a magnetic shield to prevent ac magnetic interferences on the junction. A Josephson junction is attached to the coldfinger of the cooler and a vacuum chamber is installed around the coldfinger. The temperature of the coldfinger could be kept at any value from 50K to 90K with long-term stability of 0.01K by a temperature control system. Long-term stability of the junction temperature at the level of around 10^{-4} has been found to be required for high accuracy operation of the spectrum analyzer. Active voltage biasing of the junction and time scanning of the bias are accomplished by analogue electronics, which includes a low-noise preamplifier at the coldfinger of the cooler.

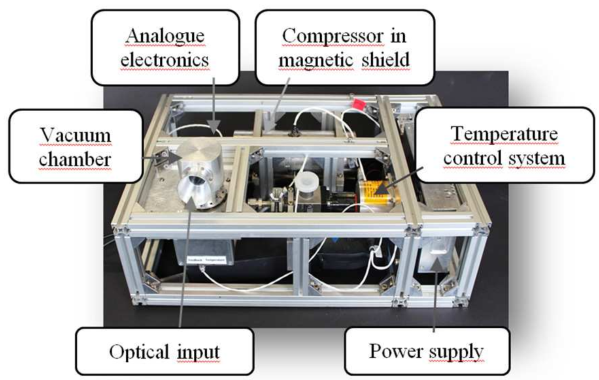


Fig.2. Photo of Hilbert-transform spectrum analyzer with $YBa_2Cu_3O_{7-x}$ bicrystal Josephson junction integrated on Stirling cooler.

Terahertz radiation with spectrum $S(f)$ is coming through an optical window in the vacuum chamber around the coldfinger. The response ΔI, induced by modulated THz radiation, is amplified in the electronic unit and transformed to the dc signal by an external lock-in amplifier. The time-dependent signals, proportional to the junction voltage $V(t)$, the current $I_0(t)$ and the response $\Delta V(V)$, are simultaneously digitized by a data acquisition system and transferred to a personal computer for calculations of the spectrum $S(f)$.

IV. Instrumental function

An instrumental function is a main characteristic of a spectroscopic device. Actually, the development of the Hilbert-transform spectral analysis was stimulated by a need to measure the instrumental function of the far-infrared grating spectrometer and actually the results of the measurements of this instrumental function was the first terahertz application of the Hilbert-transform technique [14]. Later, a Lorentz form of the instrumental function of the Hilbert-transform spectrum analyzer was several times experimentally established [15]-[17]. After experimental evidences, the instrumental function was also theoretically considered and the Lorentz form was deduced [11].

An instrumental function of the developed spectrum analyzer was studied and the responses $\Delta V(V)$ of the $YBa_2Cu_3O_{7-x}$ Josephson junction to monochromatic radiation with the frequencies in the range from 70 GHz of 2 THz were processed according to the algorithm of Hilbert-transform spectral analysis. To get a single-frequency operational mode of the available THz sources, like harmonic multipliers and optically-pumped lasers, their output spectra have been measured by Hilbert-transform spectrum analyzer as a function of adjustable parameters (see the next chapter). Two THz radiation sources were chosen for the measurements of the instrumental function, namely, an x5 frequency multiplier pumped by 94GHz Gunn oscillator and an optically-pumped CH_3OH laser with the output frequency of 1.75753 THz. The experiments were carried out at rather high radiation levels, but inside the power dynamic range of the Josephson detector.

The instrumental function for the radiation frequency of 470.00 GHz (Fig. 3) was found to be concentrated only in the limits of a fundamental peak at the frequency f of 470 GHz with the width δf of 2.6 GHz. The logarithmic scale is used in Fig.3 to reveal possible distortions of the instrumental function at the harmonic or subharmonic frequencies. Namely, the value of the instrumental function at the fundamental frequency of 470 GHz has been found to be of $3{\cdot}10^3$ times higher than the subharmonic signal at the frequency 235 GHz and $3{\cdot}10^2$ higher than the signal at the harmonic frequency of 940 GHz. The second figure demonstrates that the signal is still inside the power dynamic range, while the first figure shows the level of deviations of the junction from that of RSJ model.

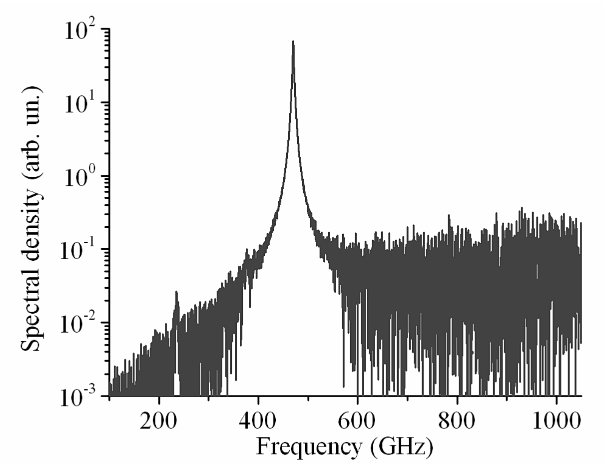


Fig. 3. Instrumental function of Hilbert-transform spectrum analyzer with $YBa_2Cu_3O_{7-x}$ bicrystal Josephson junction at 60 K. $R_n = 0.6\ \Omega$.

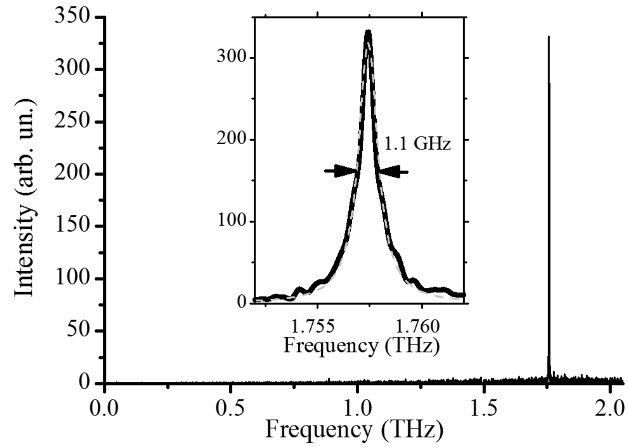


Fig. 4. Instrumental function of Hilbert-transform spectrum analyzer with $YBa_2Cu_3O_{7-x}$ bicrystal Josephson junction at 61 K. $R_n = 0.4\ \Omega$. $T = 61$ K. Inset: Instrumental function (solid line) in extended frequency range around frequency of 1.7575 THz together with Lorentz fit (dash grey line).

The instrumental function for the laser frequency of 1.75753 THz (Fig. 4) is also concentrated only in the limits of a fundamental peak at the frequency f of 1.7575 THz with the width Δf of 1.1 GHz. A shape of the instrumental function is very close to the Lorentz curve and the width is also close to the theoretical value of the Josephson linewidth δf of 1 GHz. The record value of $1.6{\cdot}10^3$ has been achieved for resolving power $f/\delta f$ of the developed THz spectrum analyzer.

To reach the resolution Δf in Fourier-transform spectroscopy, a mirror in the interferometer should be mechanically moved on a maximum distance $\Delta X \cong c/\Delta f$ [18], i.e. for Δf of 1 GHz the distance ΔX should be of around 30 cm. It is clear that this extended mechanical movement in Fourier spectroscopy requires much more time than a scan of electrical voltages of the order of a few millivolts in Hilbert spectral analysis. High spectral resolution, low distortions of the instrumental function, broad spectral range and high-speed of operation are among the main advantages of the developed Hilbert-transform spectrum analyzer. This set of parameters allow us to apply the developed spectrum analyzers in rapid and precise measurements, like detailed characterization of new THz radiation source and detection of liquids.

V. Output spectra of THz sources

A. Frequency multipliers

First examples of applications of Hilbert-transform spectrum analyzers to characterize the spectra of THz oscillators [8] were presented for the multistage frequency multipliers based on GaAs Schottky diodes [19]. We have

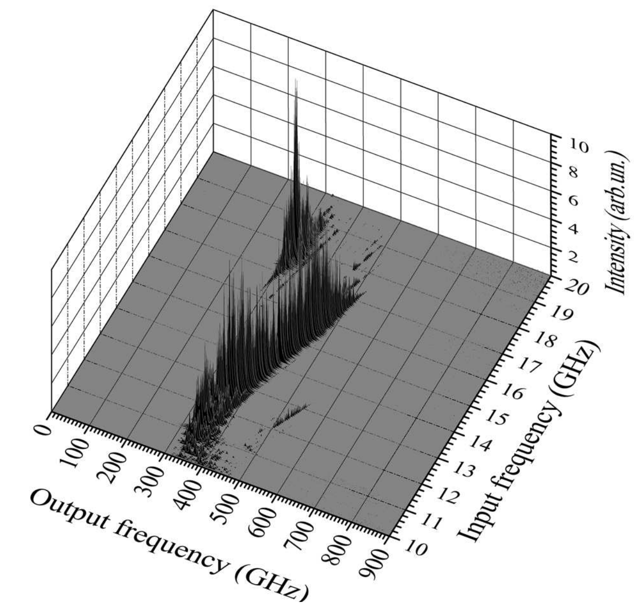


Fig. 5. Spectra $S(f_{out}, f_{in})$ of multistage frequency multiplier N1 for input frequencies from 10 to 20 GHz. Measured by Hilbert-transform spectrum analyzer with $YBa_2Cu_3O_{7-x}$ bicrystal Josephson junction of 0.6 Ω at 61 K.

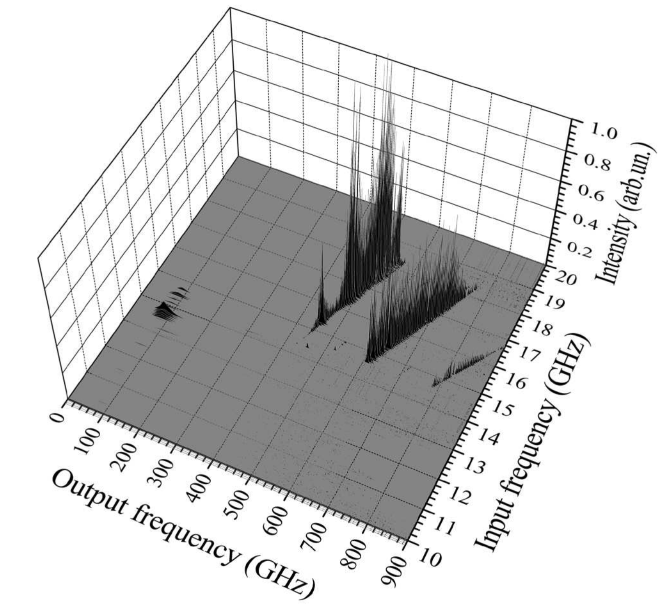


Fig. 6. Spectra $S(f_{out}, f_{in})$ of multistage frequency multipliier N2 for input frequencies from 10 to 20 GHz. Measured by Hilbert-transform spectrum analyzer with $YBa_2Cu_3O_{7-x}$ bicrystal Josephson junction of 0.6 Ω at 61 K.

extended our measurements to the multipliers based on GaAs/AlAs superlattices [20], and compared their output spectra with that of based on GaAs Schottky diodes. A microwave synthesizer with the frequencies in the range from 10 to 20 GHz was used as a primary oscillator for the multipliers. Then, an active x6-multiplier has been used to produce intensive radiation of a W-band, which served as a pump for the next stage of passive multipliers. Output radiation of the passive multipliers has always demonstrated the spectra with a rather complicated content. Even frequency components from the output of active multiplier could be detected in the output radiation, due to some leak from the waveguide flanges or dc biases, which could be canceled by proper shielding of the set-up with absorbers. Thus, Hilbert-transform spectrum analyzer could be used also for rapid quality control of multipliers.

The resulting spectra $S(f_{out}, f_{in})$ of output radiation from two multistage multipliers with passive last stages made from GaAs Schottky diodes (N1) [19] and GaAs/AlAs superlattices (N2) [20] are shown in Fig.5 and Fig. 6, correspondingly. The same Josephson junction with the resistance R_n = 0.6 Ω at the temperature of 61 K has been used in spectral analysis of both multipliers. The frequency of amplitude modulation of the pump radiation from the synthesizer was equal to 250 kHz. A time constant of a lock-in amplifier was of 100 µs.

The input frequencies f_{in} were switched manually on the frequency synthesizer with the step of 50 MHz and this manual procedure together with a manual start of the scan of the analyzer determined the time interval between the next measurements. Scanning times of each spectrum in Fig.5 and Fig.6 were of 500 ms and did not contribute significantly to the total measurement time. Earlier, Hilbert-transform spectral analysis with the scanning times as low as 50 ms has been demonstrated and due to this circumstance, very rapid characterization procedure can be realized based on Hilbert spectrum analyzer with automated initiating of scanning and switching of the f_i-settings.

The recovered spectra for the multiplier N1 (Fig.5) demonstrate the lines with the only output frequencies f_{out} $=30f_{in}$ at the input frequencies f_{in} from 13.5 to 16 GHz. Outside this range of f_{in}, there are additional weak spectral lines with higher numbers of multiplication, up to $42f_{in}$ at f_{in} from 12 to 13.5 GHz. At lower f_{in} from 10 to 11 GHz a variety of line are observed with high multiplication numbers. At high input frequencies f_{in} from 16 to 19.5 GHz additional strong lines with the frequencies f_{out} $=18f_{in}$ are observed together with weak line with other multiplication numbers. The observed harmonics in output radiation of the multiplier N1 are concentrated in the frequency range from 300 to 500 GHz, in spite of a two-fold increase of the input frequency. The output waveguide of the multiplier N1 with a cut-off frequency of around 300 GHz is responsible for a low-frequency limit of output radiation, while a very rapid decrease of the amplitudes of the harmonics for GaAs Schottky diodes with a harmonic number is responsible for the high-frequency limit.

Spectra of output radiation $S(f_{out}, f_{in})$ from the second multiplier N2 are presented in Fig. 6. They demonstrate four families of the spectral lines with the frequencies of $6f_{in}$, $30f_{in}$, $42f_{in}$, and $54f_{in}$, which correspond to multiplication factors n of 1, 5, 7 and 9 for the final stage made of GaAs/AlAs superlattices. The first family with the frequencies of $6f_{in}$ is a residue of the intensive input pump radiation, which after strong attenuation has still passed through the output waveguide.

A single-frequency output of this multiplier was not possible at any input frequencies with high harmonic numbers.

When compared with frequency multipliers made of GaAs Schottky diodes, maximum output power for the multipliers with GaAs/AlAs superlattices at the multiplication number of 5 is of around one order lower, it decreases less with the increase of the multiplication factor *n* and it requires optimization of input power in a narrow range.

It is also should be noted that Hilbert-transform spectral analysis of the high-harmonic content of the multipliers based on GaAs/AlAs superlattices gives the results in the natural form of symmetric spectral lines of positive polarity (Fig. 6). When Fourier-transform spectroscopy was used for the same multipliers [20], negative components and asymmetric lines were observed in the resulting spectra for harmonics. This effect was attributed to phase distortions for high-order harmonics coming to the interferometer with various angles to its optical axis [20]. When compared with Fourier-transform spectral analysis based on an interferometer and broadband detector, Hilbert-transform spectral analysis, which is based only on square-law Josephson detection, has an advantage to be insensitive to various phase distortions introduced by high harmonics with various numbers.

B. Optically-pumped lasers

It was not easy to optimize a single-frequency operation of the THz frequency multipliers. Also, the similar problem was found in the THz gas lasers with external tunable resonators. Several transitions between various energy levels in the excited gas can induced a number of spectral lines. Those of the lines which coincide with the resonator modes are amplified and appear at the output of the laser. A typical way to measure the spectral content of the gas laser is to scan mechanically the length of the resonator and calculate the wavelength of radiation from the detected response to output radiation vs. the resonator length. This approach works well for a single spectral line, but for a variety of the spectral lines and especially for the lines with a small difference in the frequency it requires rather extended scanning of the resonator length.

Here, we present the results of the application of developed Hilbert-transform spectrum analyzer for characterization of THz lasers. An optically-pumped laser [21] with vapors of CH_3OD was used as a source of radiation (Fig.7, left photo). Vapors of partially deuteriuated methanol in the laser were pumped by radiation from a CO_2 laser tuned to the 9R08 line. Two spectral lines with close frequencies of 0.9806 and 1.0169 THz are expected from the laser output according to the specification. Output radiation of the laser was modulated by a 20kHz optical chopper placed between two parabolic mirrors. Modulated laser radiation was focused on the input of Hilbert-transform spectrum analyzer as shown in Fig.7. The length of the laser resonator was controlled by a step motor.

Output spectra of the CH_3OD optically-pumped laser are presented in Fig.7 (right). The length of the laser resonator has been tuned with a step of 1 µm and corresponding spectra have been measured by Hilbert-transform spectrum analyzer with the scanning time of a few seconds. As it follows from Fig.7, it possible to control the spectra of the laser and optimize a single-frequency operation of the laser either on the spectral line with the frequency of 0.981 THz or 1.017 THz. Also, it is found with the spectrum analyzer that these two spectral lines can appear in the output of laser at some intermediate tuning of the resonator length.

It will take much more time to resolve the difference between these two lines using only the length tuning of the resonator and detecting the output signal with some THz detector. In this case the length tuning of range of around 10 millimeters will be required to get an interferogram, from which one can calculate the difference in the wavelength of the two closely-spaced spectral lines. As it can be seen from Fig.7, it requires the step of 1 µm to resolve the maximum output of 1THz radiation from the laser. That means one might need around 10^4 points in the interferogram to be measured with mechanical scanning of the resonator length that might take a few minutes to achieve. With Hilbert-transform technique the spectral content of the output radiation of the laser might be measured in a few seconds.

C. Polychromatic source

Starting from the spectra of radiation sources measured and optimized with Hilbert-transform spectrum analyzer, we have

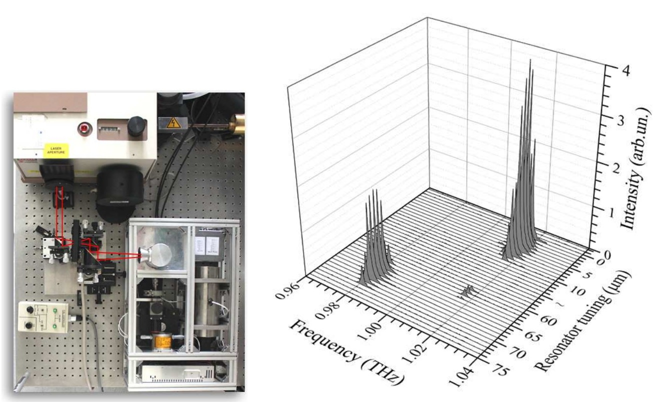


Fig. 7. Photo of Hilbert-transform spectrum analyzer at the output of an optically-pumped THz laser (left) and spectra of output radiation (lines at 0.981 and 1.017 THz) of the laser with CH_3OD inside vs. tuning of a laser resonator from 0 to 72 µm (right).

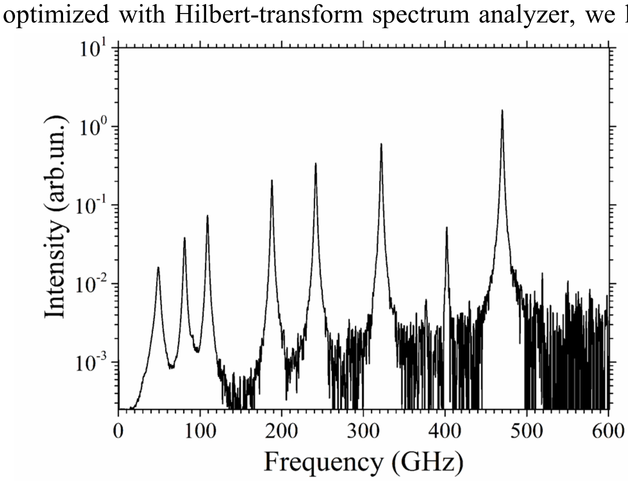


Fig.8. Spectrum of polychromatic source based on a set of frequency multipliers and intended for reflection measurements. Measured with Hilbert-transform spectrum analyzer.

synthesized a polychromatic source with a set of spectral lines ranging from 50 to 500 GHz. The polychromatic source is intended for reflectance measurements together with Hilbert-transform spectrum analyzer and is used in a set-up for identification of liquids. A construction of the polychromatic source and the reflectance spectra measured with this source and Hilbert spectrum analyzer will be published elsewhere [22]. A set of frequency multipliers has been optimized with Hilbert-transform spectrum analyzer and combined into one beam. The resulting spectrum is presented in Fig.8.

Each spectral line in the spectrum in Fig.8 has been optimized in intensity so that no harmonic or subharmonic frequency components appear in the spectrum. It was found possible to get the intensities close to three orders above the noise level for each frequency component in the spectrum in Fig.8. The combination of this polychromatic source and Hilbert transform spectrum analyzer allow measuring the reflectivity of the samples with the accuracy of a few tenths of a percent in the frequency range from 50 to 500 GHz. With this combination of the source and the spectrum analyzer the reflection spectra of the ethanol/water mixtures have been measured and a residual content of alcohol in alcohol-free beer has been detected [22].

VI. Conclusion

Based on the recent progress in high-T_c Josephson technology and Hilbert-transform spectrum analysis, a demonstrator of Hilbert-transform spectrum analyzer has been developed and tested with various THz radiation sources. Invisible cooling of the high-Tc Josephson junction with maintanence-free Stirling cooler is accomplished in this spectrum analyzer. The resolving spectral power $f/\Delta f$ of $1.6{\cdot}10^3$ and absence of the subharmonic and garmonic contriburions in the instrumental function at the level of better than $5{\cdot}10^{-3}$ have been demonstrated for the spectrum analyzer in the THz range.

Spectra of output radiation of THz frequency multipliers and gas lasers has been measured with subsecond scan times and a control of a single-frequency operation of these sources has been demonstrated with this spectrum analyzer. A polychtomatic radiation source operationg in the spectral range is synthesized under control of Hilbert-transform spectrum analyzer. A combination of this polychromatic source and developed spectrum analyzer is very perspective for rapid and accurate reflection measurements of liquids.

Hilbert-transform spectral analysis based only on a square-law Josephson detector has a number of advantages when compared with a conventional Fourier-transform technique, based on an optical interferometer and a liquid-helium cooled bolometer. Hilbert-transform spectral analysis is considered as a substitute of the Fourier-transform technique in demanding rapid and accurate THz application like spectral characterization of new THz radiation source, plasma diagnostics and public security.

References

[1] M. Tonouchi, "Cutting-edge terahertz technology," *Nature Photon.,* vol. 1, pp. 97–105, 2007.

[2] Terahertz Radiation Systems: Technologies and Global Markets. BCC Research Report No. IAS029B, March 2012. http://www.bccresearch.com/report/terahertz-radiation-systems-ias029a.html

[3] S. Anders et al. "European roadmap on superconducting electronics – status and perspective," *Physica C,* vol. 470, pp. 2079-2126, 2010.

[4] K. K. Likharev, Dynamics of Josephson Junctions and Circuits, NewYork: Gordon and Breach, 1986.

[5] Y. Divin, U. Poppe, V.N. Gubankov, K. Urban, "High-T_c Josephson Detectors and Hilbert Spectroscopy for Security Applications", *IEEE Sensors J.*, vol.8, pp.750-757, 2008.

[6] Y. Divin, H.K.B. Pandya, "Feasibility of ECE measurements using Hilbert-transform spectral analysis", *Fusion Science and Technol.,* accepted for published.

[7] http://www.aim-ir.com/

[8] Y. Divin, M. Lyatti, A. Snezhko, U. Poppe, and V. Pavlovskiy, "THz Hilbert-Transform Spectrum Analyzer Based on High-T_c Josephson Junction in Stirling Cryocooler", *IEEE Trans. Appl. Supercond*., vol. 23, no. 3, 1800204, June 2013.

[9] Y.Y. Divin, O.Y. Polyanskii, A.Y. Shul'man, "Incoherent radiation spectroscopy by means of the Josephson effect," *Sov. Tech. Phys. Lett.* (Engl. Transl.), (United States), vol.6, no.9, pp.454-455, 1980

[10] F. W. King, *Hilbert Transforms,* vol 1. Cambridge University Press, 2009, pp. 252-287. http://dx.doi.org/10.1017/CBO9780511721458

[11] A.Ya. Shul'man, E.L. Kosarev, M.A. Tarasov, "Hilbert-transform spectroscopy based on the ac Josephson effect. Theory and computational technique." *J. Comm. Electron. Technology*, vol.48, pp.1124-1136, 2003.

[12] Y.Y. Divin, A.V. Snezhko, M.V. Lyatti, V.V. Pavlovskiy. "Terahertz Hilbert-transform spectral analysis" (to be published).

[13] Yu. Ya. Divin, U. Poppe, I. M. Kotelyanskii, V. N. Gubankov, and K. Urban, "Terahertz Spectroscopy Based on Josephson High-Temperature Superconductor Junctions", *J. Commun. Technol. Electronics*, vol. 53, no. 10, pp. 1137–1152, 2008.

[14] Yu.Ya. Divin, O.Yu. Polyanskii, A.Ya. Shulman, "Real instrumental function of a grating monochromator," *Optics and Spectroscopy*, vol.47, no.1, pp.95-101, July 1979.

[15] Yu.Ya. Divin, H. Schulz, U. Poppe, N. Klein, K. Urban, V.V. Pavlovskii, "Millimeter-wave Hilbert-transform spectroscopy with high-T_c Josephson junctions," *Appl. Phys. Lett*., vol.68, no.11, pp.1561-1563, 1996.

[16] Y.Y. Divin., I.M. Kotelyanskii, P.M. Shadrin, O.Y. Volkov, V.V. Shirotov, V.N. Gubankov, H. Schulz, U. Poppe, "$YBa_2Cu_3O_{7-x}$ Josephson junctions on $NdGaO_3$ bicrystal substrates", *Applied Superconductivity 1997.* Proceedings of EUCAS 97. Ed.: H.Rogalla and D.H.A. Blank, Inst. of Physics Conf. Ser. No.158, IOP Publishing Ltd., Bristol & Philadelphia, vol.1, pp.467-471, 1997.

[17] Y. Divin, O. Volkov, V. Pavlovskii, V. Shirotov, P. Shadrin, U. Poppe, K. Urban, "Terahertz Hilbert spectroscopy by high-T_c Josephson junctions", in Advances in Solid State Physics, ed. B. Kramer (Springer, Berlin, Germany), vol.41, pp. 301-313, 2001.

[18] G.W. Chantry. *Submillimetre Spectroscopy*. London and New York: Academic Press; 1971.

[19] Model FM5-500, Radiometer Physics GmbH, Germany.

[20] D. G. Paveliev, Y. I. Koshurinov, A. S. Ivanov, A. N. Panin, V. L. Vax, V. I. Gavrilenko, A. V. Antonov, V. M. Ustinov, A. E. Zhukov, "Experimental study of frequency multipliers based on a GaAs/AlAs semiconductor superlattices in the terahertz frequency range", Semiconductors, vol. 46(1), pp. 121–125, 2012.

[21] Model FIRL 100, Edinburgh Instruments Ltd., Scotland.

[22] Y. Divin, A. Snezhko, U. Poppe, I. Gundareva, V. Pavlovskiy, "Screening of liquids with quasioptical high-T_c Josephson detectors," Proc. NATO Adv. Research Workshop *Nanotechnology in the security systems*, Ed. S. Kruchinin, Yalta, Ukraine, Sept. 29 - Oct. 3, 2013 (to be published).

Yuriy Divin (M'97) was born in Chernyakhovsk, Russian Federation, in 1948. He studied physics at the Moscow Institute of Physics and Technology and received the Diploma degree in physics in 1972, the Ph.D. degree in electronics from the Institute of Radio Engineering and Electronics of Russian Academy of Sciences (IRE RAS) in 1979 and the Dr.Sc. degree from the Kotel'nikov IRE RAS, Moscow, Russia, in 2011.

Since 1986, he has been employed as a Senior Research Scientist and since 2011 – a Leading Research Scientist at the Kotel'nikov IRE RAS and a Group Leader. In 1983, 1984, 1991, and 1992, he was a Guest Scientist at the Physics Department of the Technical University of Denmark, and from 1993 to 1998, he was a Guest Scientist at the Forschungszentrum Jülich, Germany. Since 1998, he has been employed as a member of scientific staff at the Institute for Solid State Research at the Forschungszentrum Jülich.

Since 1970, his scientific interests were in the field of superconducting electronics, especially in the applications of the ac Josephson effect for detection, spectroscopy, and imaging of electromagnetic radiation. Current research interests are within physics, technology and terahertz applications of high-T_c Josephson junctions. He is the author of more than 140 articles, and 7 inventions.

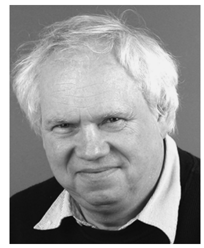
Dr. Y. Divin is a member of IEEE since 1997 and a member of ESAS since 1998.

Alexander Snezhko was born in Volgodonsk, Russian Federation, in 1990. He received the B.S. and M.S. degrees in applied physics and mathematics from Moscow Institute of Physics and Technology (MIPT), Russia, in 2011 and in 2013, correspondingly. At present time A. Snezhko is a Ph.D. student in applied physics and mathematics from MIPT.

Since 2010, he is an Engineer in Kotel'nikov Institute of Radioengineering and Electronics of Russian Academy of Sciencies, Moscow. Since 2012, he is an Assistant Student with the Peter Grünberg Institute, Forschungszentrum Jülich in compliance with agreement between Kotel'nikov Institute of Radioengineering and Electronics of Russian Academy of Sciencies and Forschungszentrum Jülich. His research interests include applied superconductivity, solid state physics, Josephson junctions in detecting and spectroscopy of lectromagnetic radiations at terahertz frequencies, low noise electronics.

Matvey Lyatti was born in Petrozavodsk, Russian Federation, in 1978. He received the B.S. and M.S. degrees in applied physics and mathematics from Moscow Institute of Physics and Technology (MIPT), Russia, in 1999 and in 2001, correspondingly. In 2007, he received the Ph.D. degree from the Institute of Radio Engineering and Electronics of Russian Academy of Sciences (IRE RAS).

Since 2005, he has been employed as a Research Scientists and since 2012, as a Senior Research Scientist at the Kotel'nikov IRE RAS. During 2001-2004, he was involved in Ph.D. research work at the Institute for Microstructure Research, Forschungszentrum Jülich, Germany. Since 2009, he has been a Guest Scientist at the Forschungszentrum Jülich, Germany.



Ulrich Poppe was born in Leipzig, Germany, in 1948. He studied physics at the University of Cologne and received the Diploma degree in theoretical solid-state physics in 1976 and the Ph.D. degree from the University of Cologne and the Research Centre Juelich, Juelich, Germany, in 1979, for "Tunneling Experiments on Chevrel-phase-Superconductors."

Since 1979, he has been with the Institute for Solid State Research at the Research Centre Juelich. Until 1987, he worked in the low-temperature and superconductivity group on tunneling experiments on magnetic-, organic and heavy fermion-superconductors. Later, he became a Group Leader in the Institute for Microstructure Research at the Research Centre Juelich. Since 1987, his scientific interests and research areas included the following topics: scanning tunneling microscopy and studies on dislocations on GaAs, InP and Si surfaces, development of an in situ sputtering deposition method at high oxygen pressures for epitaxial high-T_c superconductor and other oxide thin films, studies on high-T_c superconducting quantum interference devices (SQUIDs) for magnetometers and gradiometers on the basis of ramp and grain boundary type Josephson junctions, high-T_c-SQUID-microscopy, development of high-T_c Josephson junctions suitable for detection and spectroscopy of millimeter- and submillimeter-wave radiation, deposition and study of epitaxial heterostructures of ferroelectric and magnetic oxides.

Dr. Poppe is a member of the German Physics Society (DPG).

Valery Pavlovskiy was born in Moscow, Russian Federation in 1959. He received the B.S. and M.S. degrees in Moscow engineering physics institute, in 1983.

Since 1989, he has been employed as a Research Scientiest with Institute of Radio Engineering and Electronics of Russian Academy of Sciences. He is the author of more than 30 articles. His research interests include computational condensed matter physics and superconductivity.