


Superconducting Terahertz Sources with 12% Power Efficiency

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 (Received 15 February 2021; revised 30 August 2021; accepted 11 November 2021; published 10 December 2021)

Low power efficiency is one of the main problems of terahertz (THz) sources, colloquially known as “the THz gap.” In this work we present prototypes of THz devices based on whisker crystals of a high-temperature superconductor $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ with a record high-radiation power efficiency of 12% at a frequency of approximately 4 THz. We employ various on- and off-chip detection techniques and, in particular, use the radiative cooling phenomenon for accurate evaluation of the emission power. We conclude that such devices can be used for creation of tunable, monochromatic, cw, compact, and power-efficient THz sources.

DOI: [10.1103/PhysRevApplied.16.L061001](https://doi.org/10.1103/PhysRevApplied.16.L061001)

Tunable, monochromatic, cw, compact, and power-efficient sources of terahertz (THz) electromagnetic waves (EMW) are required for a broad variety of applications such as spectroscopy, environmental control, security, non-ionizing medical imaging, ultrahigh-speed telecommunication and electronics, as well as for fundamental research in various areas of science [1,2]. The key problem of THz sources, colloquially known as the “THz gap,” is a rapid decay of radiation power efficiency (RPE), i.e., the ratio of emitted and dissipated power [3], in the low THz range [1]. Despite a significant progress achieved in development of semiconducting quantum cascade lasers (QCLs) [4–6], the RPE of cw QCLs drops from $\simeq 28\%$ at $f \simeq 55$ THz [7] to a subpercent at 3–4 THz [8,9] and to approximately 0.01% at $f \simeq 1.3$ THz [10]. Although QCL frequency can be tuned [4,5,9,11,12], this comes at the expense of a dramatic reduction of RPE to approximately 0.0001% [11] when low THz emission is obtained by mixing or down-conversion of higher frequencies [11,12]. QCLs emitting at primary low THz frequencies, on the other hand, have to be cooled down to cryogenic temperatures, $k_B T \lesssim hf$ [8–10].

Superconducting devices, based on arrays of Josephson junctions (JJs) have an inherent frequency tunability and provide an alternative technology for creation

of cryogenic THz sources with tunable, monochromatic cw operation [13–30]. The Josephson frequency, $f_J = (2e/h)V$, is proportional to the dc-bias voltage V and is limited only by the superconducting energy gap, which can be in excess of 30 THz for high- T_c superconductors [31,32]. Emission with a sub-mW power at $f \simeq 0.5$ THz was achieved from large-area mesa structures etched on top of single crystals of a layered cuprate superconductor $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Bi-2212) [17]. Such mesas represent stacks of atomic scale intrinsic JJs [33]. Tunable EMW emission at the primary Josephson frequency in the whole THz range 1–11 THz has been reported from small-area Bi-2212 mesas [21], albeit with a lower power. The RPE for both large [17] and small [21] mesas on Bi-2212 single crystals is $\lesssim 1\%$, which is decent for THz sources, but small compared to the theoretical limit of 50% [34]. The suboptimal operation is caused by impedance mismatching between a device and open space. Another key limitation for all cryogenic devices is set by self-heating. Taking into account limited cooling power of compact cryorefrigerators (sub-Watt at low T), devices with RPE 1% would not be able to emit much more than 1 mW. Therefore, further enhancement of the emission power from compact cryogenic devices may only be achieved via enhancement of RPE.

Here we present prototypes of THz sources based on Bi-2212 whisker-type crystals with intermediate-size mesa structures. We employ various techniques for detection of THz radiation such as *in situ* detection by a mesa on the same whisker, on-chip detection by electrically isolated mesa, and off-chip detection by a bolometer. Furthermore, we employ the radiative cooling phenomenon for estimation of the absolute value of emitted power. It reveals that

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the RPE of our devices can reach 12% making a significant step forward towards the theoretical limit of 50%. The boost of efficiency is attributed to good impedance matching with open space, caused by a specific turnstile antennalike geometry of our devices. We conclude that such devices can be used for creation of tunable, and, what is more, power-efficient cw THz sources.

Figures 1(a) and 1(b) show an image and a sketch of studied devices. In the middle of each device there is a Bi-2212 whisker with typical sizes $(300 - 500) \times (20 - 30) \times (1 - 5) \mu\text{m}^3$ along crystallographic a , b , and c axes, respectively. Several metallic electrodes with the width $10 - 15 \mu\text{m}$ are made across the whisker. Beneath each electrode there is a mesa structure containing $N \sim 150 - 250$ intrinsic JJs. Devices are made by conventional microfabrication techniques. Details about sample fabrication and the experimental setup can be found in Refs. [21,32] and the Supplemental Material [35].

Figure 1(c) shows the current-voltage (I - V) characteristics of a mesa at $T \simeq 3$ K. It consists of multiple branches, due to one-by-one switching of JJs from the superconducting to the resistive state [31–33]. The total number of JJs, $N \simeq 150 \pm 10$ for this mesa, is obtained by counting

branches. A rough estimation, valid for all our mesas is $N \simeq V_{\text{max}}/10$ mV, where V_{max} is the voltage at a maximum in the I - V . The maximum is caused by back bending at high bias due to self-heating. The extent of self-heating depends on geometry and decreases with decreasing mesa sizes [36,37]. Sizes of our mesas are in the range $(2.5 - 10) \times (10 - 30) \mu\text{m}^2$ with areas $50 < A < 300 \mu\text{m}^2$, which are significantly smaller than “large” mesas ($A > 10^4 \mu\text{m}^2$) studied in the majority of earlier works [16–20,23–29], but larger than “small” mesas ($A \lesssim 10 \mu\text{m}^2$) studied in Ref. [21]. Thus, our mesas are of “intermediate size.” This enables a significant overall power approximately 1 mW with a tolerable self-heating.

To analyze EMW emission, we start with an on-chip generation-detection scheme [21] using one mesa as a generator and another mesa on the same chip as a switching-current detector. Figure 1(d) shows evolution of the I - V s of the detector at three bias points ($I_{\text{gen}}, V_{\text{gen}}$) in the generator. The I - V of the generator mesa, with marked bias points, is shown in the top panel of Fig. 2(a). From Fig. 1(d) it is seen that with increasing bias in the generator, critical currents in the detector are first reduced (red curve) and then get completely suppressed (blue curve)

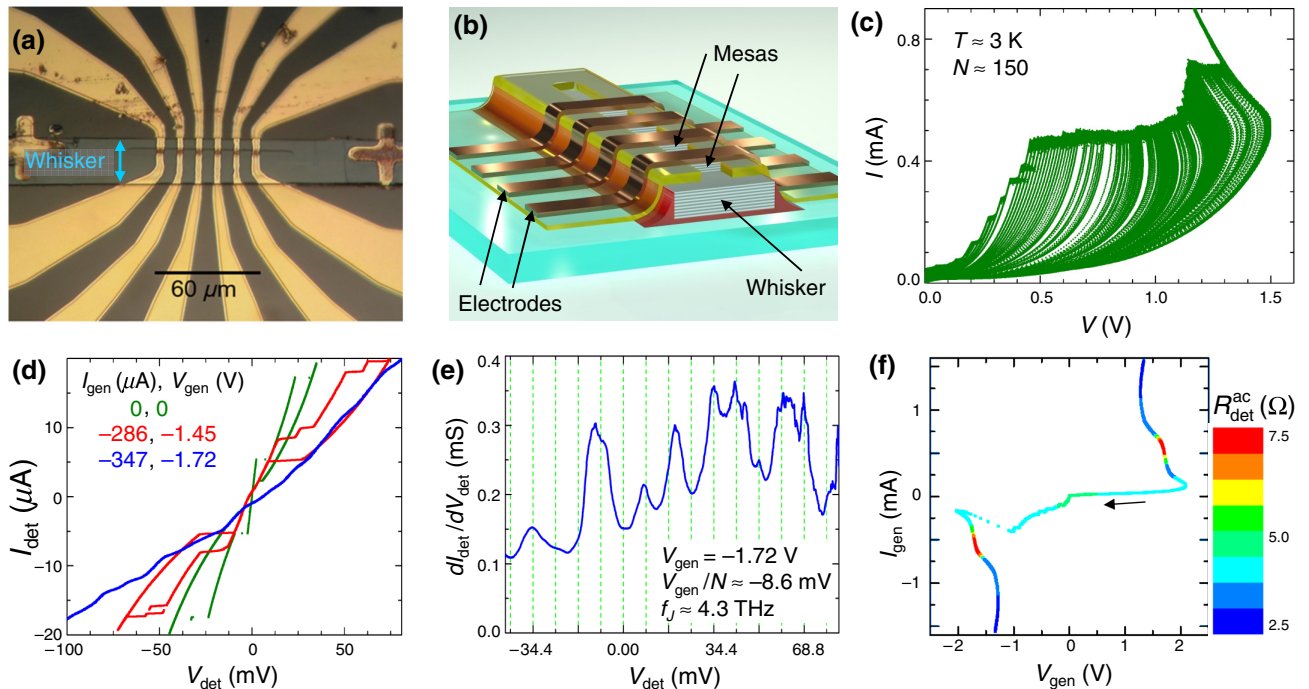


FIG. 1. (a) Optical image of one of the studied devices. Six mesas are formed beneath gold electrodes. (b) Sketch of the device. (c) I - V characteristics (integrated oscillogram) of a mesa. Multiple branches correspond to switching of individual, $N \simeq 150$, JJs from the superconducting to the resistive state. (d) The I - V curves of a detector mesa at three bias points in the generator, marked by circles in Fig. 2(a). (e) Differential conductance of the blue I - V from (d). Peaks represent current steps. Grid lines correspond to expected Shapiro-step voltages. (f) On-chip generation-detection experiment with electrically disconnected mesas: Here we plot I - V of the generator mesa, color mapped by the ac resistance of electrically separated detector mesa on the same chip. The black arrow indicates the bias sweep direction. It is seen that the emission (red color) occurs at steps in the I - V .

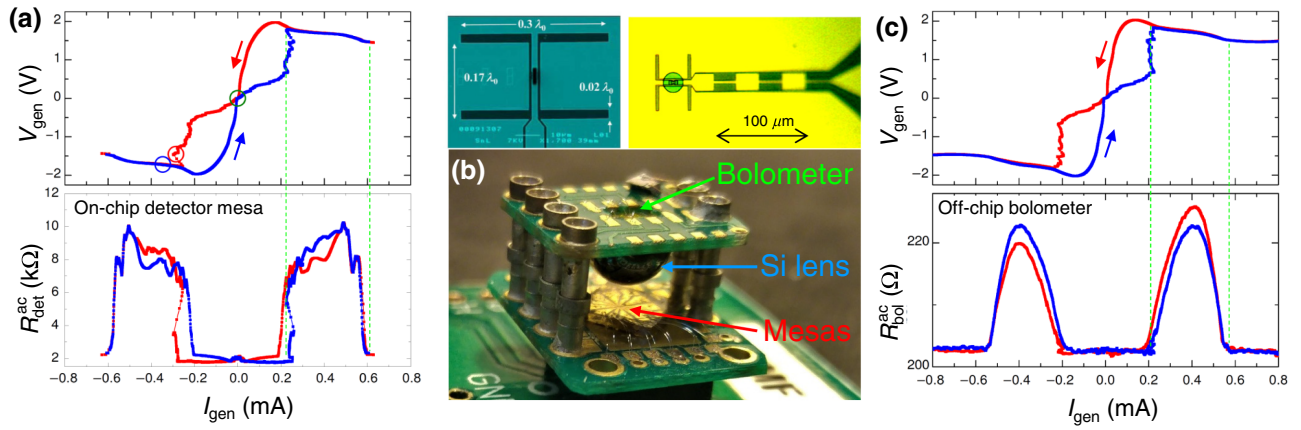


FIG. 2. Comparison of on-chip and off-chip detection schemes. (a) On-chip generation detection with electrically connected mesas. Top: the V - I of a generator mesa at $T \simeq 3$ K. Circles represent bias points for the detector I - V s in Fig. 1(d). Bottom: ac resistance of the detector mesa as a function of the generator current. Blue and red curves represent up and down bias sweeps. (b) A setup for off-chip detection of emission by a NbN bolometer and images of the bolometer (from Refs. [38,39]). (c) Off-chip detection experiment. Top: the V - I of the generator mesa. Bottom: the bolometer response as a function of I_{gen} . Vertical dashed lines in (a),(c) indicate that emission occurs at the step in the generator I - V .

due to the EMW absorption [21]. Detailed dynamics of the generation-detection experiment is demonstrated in Video S1 within the Supplemental Material [35].

Absorption of EMW by a JJ leads to formation of Shapiro steps in the I - V at $V_n = nhf/2e$ (n integer). Thus, junction response carries a spectroscopic information both about the frequency and the amplitude of EMW. In mesas with N JJs, the EMW emission occurs at $f_J = 2eV_{\text{gen}}/Nh$ (provided all JJs are synchronized). Thus, the primary Shapiro step should appear at $V_{\text{det}} = V_{\text{gen}}/N$. Small steps can indeed be seen in the blue I - V from Fig. 1(d). Figure 1(e) shows the differential conductance for this curve. It exhibits clear peaks, corresponding to steps in the I - V . The grid spacing is equal to V_{gen}/N with estimated $N \simeq 200$ for the generator mesa, see Fig. 2(a), and is in agreement with the observed peak separation. Some displacement of peak positions is likely caused by the fact that the detector response involves six JJs, see Fig. 1(d). A certain difference between JJs leads to a mismatch of bias conditions for appearance of Shapiro steps. This affects both the regularity and the amplitude of Shapiro steps. Nevertheless, the data is consistent with occurrence of monochromatic emission at $f_J \simeq 4.3$ THz because the non-monochromatic emission would not lead to appearance of distinct steps.

To exclude possible electrical crosstalk, we perform a similar generation-detection experiment using electrically disconnected mesas. For this the whisker is cut by a focused ion beam in two sections, thus separating the generator and the detector mesas. The detector response remains qualitatively unchanged after such separation. Figure 1(f) shows the I - V of the generator mesa, color mapped by the response of electrically disconnected

detector mesa (ac resistance, $R_{\text{det}}^{\text{ac}}$, measured by the lock-in technique with zero offset). It is seen that a profound, almost vertical step develops in the back-bending region of the I - V . The color code indicates that the detector response appears just at this step and disappears both above and below. In Fig. 2(a) the same behavior is demonstrated for the on-chip generation-detection experiment with electrically connected mesas. Here a correlation between the step in the I - V of the generator and the upturn in the detector response is clearly seen (see also Video S1 within the Supplemental Material [35]). Such a nonmonotonic behavior precludes the self-heating origin of the observed signal and confirms occurrence of the EMW emission [21].

To confirm EMW emission into open space we perform off-chip detection using a NbN bolometer [38]. Figure 2(b) shows the measurement setup and images of the bolometer. The bolometer is placed at a distance approximately 1 cm above the device. Figure 2(c) shows corresponding generation (top) and detection (bottom) characteristics. Vertical dashed lines indicate that the bolometer response (lock-in resistance $R_{\text{bol}}^{\text{ac}}$) appears at the step in the I_{gen} - V_{gen} , thus confirming EMW emission. Some difference in the shapes of on-chip, Fig. 2(a), and off-chip, Fig. 2(c), responses is likely caused by the spectral selectivity of the double-slot antenna of the bolometer, peaked at $f \simeq 1.6$ THz, well below the emission frequency $f_J \simeq 4.2$ THz for this mesa [40].

Power dissipation leads to heating, but EMW emission—to radiative cooling of the device. We use this for unambiguous estimation of the emission power, P_{THz} . Figure 3(a) represents the on-chip generation-detection measurement for another device (upward bias sweep). The sample stage of our dry cryostat has a relatively small heat

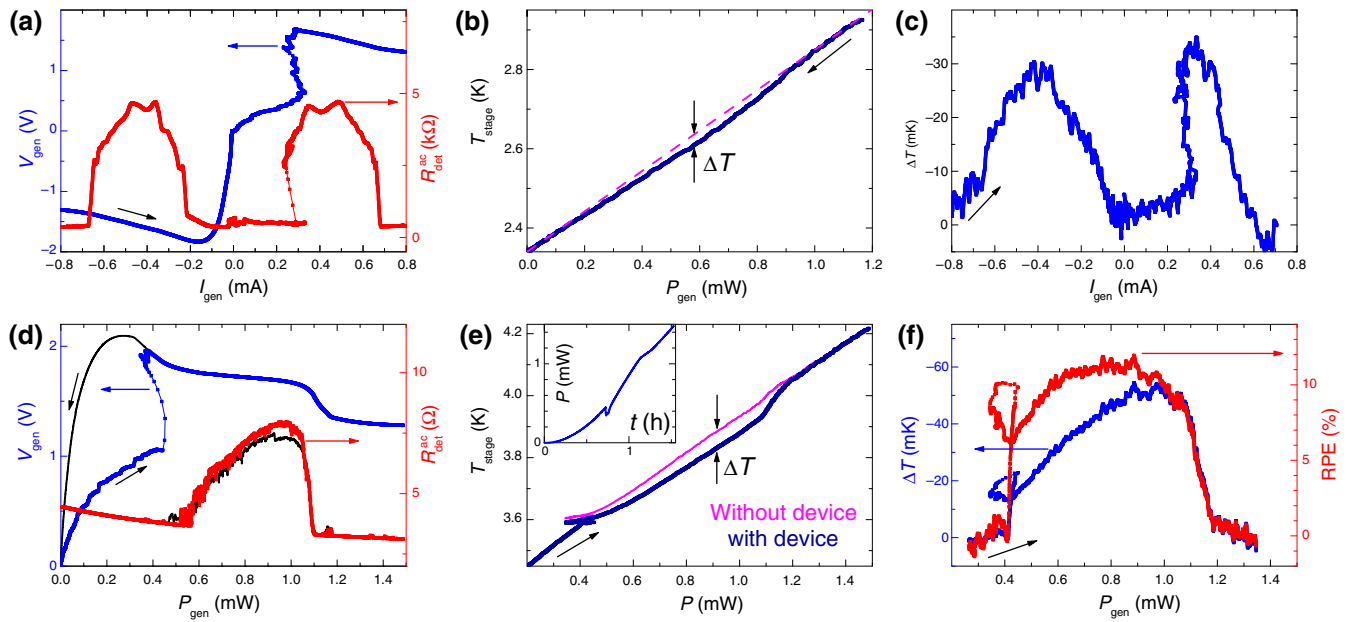


FIG. 3. The radiative cooling analysis for two devices (a)–(c) and (d)–(f). (a) The generator V - I (blue, left axis) and the on-chip detector response (red, right axis) versus I_{gen} . (b) The stage temperature (dark blue) versus the dissipation power P_{gen} for an upward bias sweep ($I_{\text{gen}} < 0$). It deviates from the linear dependence (magenta dashed line) at $P_{\text{gen}} \simeq 0.6$ mW. (c) The temperature drop versus I_{gen} . It is seen that ΔT is correlated with the detector response in (a). (d) The generator mesa voltage (blue, left axis) and the detector response (red, right axis) vs P_{gen} for another device (an upward bias sweep). Black lines correspond to the reverse sweep. (e) T_{stage} versus the dissipation power for experiments with (dark blue) and without (magenta) device for upward bias sweeps. The inset shows time dependencies of the dissipation power, identical for both cases. (f) Temperature drop (blue, left axis) and radiation power efficiency (red, right axis) versus P_{gen} . It is seen that RPE reaches 12%.

capacitance and a finite heat resistance, R_{th} , to the cold-head. Therefore, its temperature directly reflects the energy balance at the chip. Figure 3(b) shows the stage temperature as a function of the dissipation power, $P_{\text{gen}} = I_{\text{gen}}V_{\text{gen}}$, for the data from Fig. 3(a). As expected from Newton’s law of cooling, it increases approximately linearly, $T_{\text{stage}} \simeq T_0 + R_{\text{th}}P_{\text{gen}}$, with $R_{\text{th}} = 0.508$ K/mW. However, at $P_{\text{gen}} \simeq 0.6$ mW there is a visible drop down from the linear dependence. In Fig. 3(c) we plot this drop, ΔT , versus I_{gen} . It clearly follows the detector response, shown by the red line in Fig. 3(a). The correlation between ΔT and the EMW emission provides a straightforward demonstration of the radiative cooling phenomenon. It is worthwhile to note, it allows direct estimation of $P_{\text{THz}} = \Delta T/R_{\text{th}}$. The maximum drop $\Delta T = -31.5 \pm 2$ mK occurs at $I_{\text{gen}} \simeq 0.4$ mA and $P_{\text{gen}} = 0.6$ mW. This yields $P_{\text{THz}} \simeq 62$ μ W and RPE of $10.3 \pm 0.7\%$ for this device.

Figures 3(d)–3(f) show similar measurements for another device. Figure 3(d) shows V_{gen} (blue, left axis) and $R_{\text{det}}^{\text{ac}}$ (red, right axis) versus P_{gen} for the upward bias sweep (black lines represent similar data for the reverse sweep). The dark blue curve in Fig. 3(e) shows T_{stage} versus P_{gen} for the upward sweep. Inset shows time dependence of $P_{\text{gen}}(t)$ during this sweep. It is nonlinear due to the non-Ohmic I - V of the generator. The nonlinearity may cause

some transient effects. Therefore, to make an accurate calibration of the bare (without device) thermal response of the stage we heat it by a resistor, applying exactly the same time dependence of the dissipation power using a programmable current source. The corresponding variation of T_{stage} is shown by the magenta line in Fig. 3(e). It is almost linear with the slope $R_{\text{th}} \simeq 0.514$ K/mW. Figure 3(f) shows the difference between T_{stage} with and without device (blue) and the radiation power efficiency $\text{RPE} = -\Delta T/(R_{\text{th}}P_{\text{gen}})$ (red curve). It is seen that the maximum RPE for this device reaches 12%, which corresponds to the emission power of $P_{\text{THz}} \simeq 0.11$ mW. We want to emphasize that this power is actually emitted in the far field. Indeed, it is taken out of the range cooled by the second stage of the cryocooler (which has a small cooling power) and is dumped into the first stage (with a very large cooling power), which is 10–40 cm away (see a sketch in Fig. S1 within the Supplemental Material [35]). This distance is much larger than the wavelength, $\lambda \sim 70$ μ m, at $f \sim 4.3$ THz. Therefore, the radiative cooling probes the total far-field emission. Of course, for the practical device the emission should be collected and delivered via open space to the desired place, which inevitably involve certain losses. In this respect the estimation of RPE from the radiative cooling provides the upper limit of the achievable “useful” emission.

Estimations above indicate that whisker-based THz sources can have RPE $> 10\%$, not far from the theoretical limit of 50% [34]. This significantly exceeds the RPE for devices made on regular Bi-2212 crystals [17,21]. Generally, the low RPE is caused by poor impedance matching with open space [34]. JJs are much smaller than the wavelength. Particularly tiny are interlayer distances of approximately 1 nm. Therefore, JJs act as miniature dipoles with almost no emission in the far field. Essentially, the emission is facilitated by other passive but large-size elements of the device such as the Bi-2212 crystal and the electrodes, acting as matching antennas. Optimization of emission requires proper microwave design for impedance matching. In the Supplemental Material [35] we discuss the geometrical differences between crystal- and whisker-based devices. We argue that the reported boost of RPE in whisker-based devices is caused by a specific turnstile antennalike geometry, which allows obviation of a large parasitic capacitance between the crystal and the electrode and facilitates good impedance matching with open space.

To conclude, a low-radiation power efficiency is one of the main problems of THz sources. For cryogenic sources the emission power is limited both by the cooling power and RPE: $P_{\text{THz}} < \text{RPE} \times P_{\text{cooling}}$. For portable cryocoolers with limited P_{cooling} , the only way to increase the emission power is by enhancement of the RPE. We present prototypes of THz sources based on $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ whiskers with RPE up to 12% , more than an order of magnitude larger than for similar devices made on regular Bi-2212 crystals. This indicates better impedance matching with open space due to the specific turnstile antennalike geometry of whisker-based devices. We conclude that such devices can be used for creation of tunable, monochromatic, cw, compact and, what is more, power-efficient THz sources.

Acknowledgments. The work is supported by the Russian Science Foundation Grant No. 19-19-00594. We are grateful to A. Agostino and M. Truccato for assistance with whisker preparation, to S. Cherednichenko for providing the bolometer and to A. Efimov and K. Shiiyanov for assistance in experiment. The paper was written during a sabbatical semester of V.M.K. at MIPT.

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