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ANTENNA ARRAYS BASED ON THE GOLOMB RULERS MADE OF COPPER AND SUPERCONDUCTING ELEMENTS

M. P. Faradzheva [1] ✉, *A. V. Prikhod'ko* [1], *O. I. Kon'kov* [2]

[1] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia;

[2] Ioffe Institute of the Russian Academy of Sciences, St. Petersburg, Russia

✉ faradzheva_mp@spbstu.ru

Abstract: The features of the amplitude behavior of the electromagnetic waves (the profile of a standing wave) reflected by antenna arrays have been studied. These arrays are Golomb rulers of different orders made of copper and HTSC structures. The dependences of the amplitude on the array's arrangement with respect to the excitation source and the receiving device, as well as on the temperature. An analysis of obtained results revealed no dips in the standing wave amplitude profile for the 3rd and 4th order Golomb rulers. It was shown that for the Golomb rulers based on HTSC structures, an observed increase in the amplitude of the received signal on their cooling was associated with the transition to the superconducting state.

Keywords: Golomb ruler, antenna array, nanostructure, high temperature superconductor

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АНТЕННЫЕ РЕШЕТКИ НА ОСНОВЕ ЛИНЕЕК ГОЛОМБА ИЗ МЕДНЫХ И СВЕРХПРОВОДЯЩИХ ЭЛЕМЕНТОВ

М. П. Фараджева [1] ✉, *А. В. Приходько* [1], *О. И. Коньков* [2]

[1] Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия;

[2] Физико-технический институт им. А.Ф. Иоффе РАН, Санкт-Петербург, Россия

✉ faradzheva_mp@spbstu.ru

Аннотация. Исследованы особенности поведения амплитуды электромагнитных волн (профиля стоячей волны), отраженных антенными решетками, которые представляют собой линейки Голомба разных порядков, изготовленные из меди и ВТСП-структур. Измерены зависимости указанной амплитуды от расположения отражающих антенных решеток по отношению к источнику возбуждения волн и приемному устройству, а также от температуры. Анализ полученных данных выявил отсутствие провалов в профиле амплитуды стоячей волны для линеек Голомба 3-го и 4-го порядков. Показано, что для линеек Голомба на основе ВТСП-структур наблюдаемое увеличение амплитуды принимаемого сигнала при их охлаждении связано с переходом таких структур в сверхпроводящее состояние.

Ключевые слова: линейка Голомба, антенная решетка, наноструктура, высокотемпературный сверхпроводник

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Introduction

The structure of the transition and near-field regions in the electromagnetic radiation produced by transmitting devices has attracted growing interest. This comes with a whole range of challenges to be addressed, for example, signal failure in cellular and similar communications in the near field or electromagnetic ecology, involving geometric calculations of buffer zones near transmission centers. Additional issues are related to increasing the efficiency of transmitters and the sensitivity of receivers [1].

However, it still remains unclear how the electromagnetic fields of arbitrary emitters vary with the distance r. Only general principles have been formulated [2], in particular, that damped oscillations are superimposed on the monotonic decrease in the wave amplitude by the law $U \sim 1/r$ in the Fresnel zone (near field). The near field of an antenna is a region where the radiative field has not yet been generated and the energy balance of the electric and magnetic fields has not been established. On the other hand, the near field of an antenna with a large aperture (Fresnel diffraction zone) is determined by the dependence of the wave amplitude U on the distance, different from $U \sim 1/r$, with the option for focusing radiation at a given distance [3]. Measurements in the near field can be rather complicated because no reference calibration method has been developed. The International Electrotechnical Commission is currently working on a draft for the standard for measuring high-frequency electromagnetic fields (9 kHz to 300 GHz), especially in the near field [4].

Unequally spaced active phase-locked antenna arrays (AAs) have recently sparked a lot of attention [5, 6].

Unequally spaced linear AAs reduce the number of antenna elements without noticeable loss of resolution, preserving a low level of sidelobes. A possible type of an unequally spaced AA is the Golomb ruler [7]. Antennas in the form of Golomb rulers with a certain configuration can be found, for example, at base stations of CDMA cellular networks and in radio telescopes [8, 9].

A qualitative leap is provided through microwave devices based on high-temperature superconductors (HTSC). According to estimates, only HTSC-based passive microwave devices can reduce the noise temperature by two orders of magnitude, therefore improving the sensitivity and selectivity with a decrease in signal power and a decrease in distortion [10, 11].

Advances in HTSC materials with very low surface resistance and low losses, producing antennas with increased efficiency, have given an impetus to recent research on electrically small passive antennas (ESA). These antennas require an external feed; they are essentially a reflective screen and are commonly used in combination with lenses or reflectors. The fundamentals on passive small antennas, including superconducting ones, are presented in [12].

The state of the art in superconductive electronics is described in detail in [13], focusing particularly on reflecting and absorbing shields.

The goal of this study was to develop new methods for constructing unequally spaced passive antenna arrays based on HTSC nanostructures in various configurations (orders) of the Golomb ruler.

Measurement technique

In line with the above goal, we studied the amplitude of the electromagnetic wave (standing wave profile) depending on the position of the reflecting antenna array relative to the source of wave excitation and the receiver. The technical aspects of the experiment with a microwave excitation source are described in [14] (see Fig. 1); the technique proved to be effective for analysis of the results obtained in microwave studies [15, 16].

The experimental method consists in measuring the relative power of the electromagnetic field in the near field and in the transition region for the reflecting element, i.e., sample *3* (see Fig. 1,*a*) depending on the coordinate x of the reflecting AA relative to the wave excitation source and the receiving device. We considered the standing wave profiles with the interference of direct signals and those reflected from the sample surfaces; the latter signals were transmitted from the radiating slot in the waveguide at a frequency of 45.26 GHz.

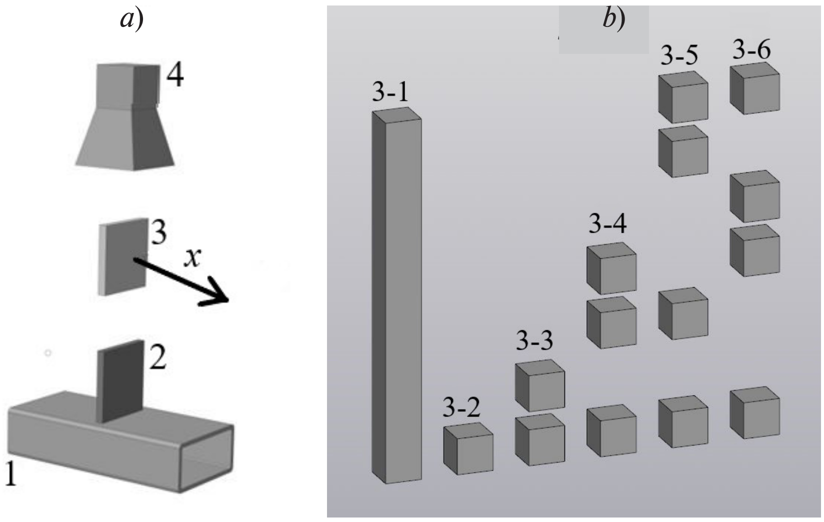

Fig. 1. Schematic diagram of the experiment (*a*) and the samples *3* used (*b*):
waveguide *1*, silicon antenna *2*, sample *3*, receiving horn *4*; solid rod antenna *3-1*,
Golomb rulers *3-2*–*3-5* of the 1st, 2nd, 3rd and 4th orders, respectively,
unequally spaced rod antenna *3*–*6* (not a Golomb ruler, see the explanations in the text);
sample displacement coordinate *x*

The setup for microwave studies in the 8-mm wavelength range (45.26 GHz) comprises waveguide *1*, silicon antenna *2* enhancing the efficiency of the radiating slot (0.5 × 10 mm) in the wall of the waveguide, holder with sample *3* and horn antenna *4*. The sample in the holder is displaced with respect to the coordinate *x* along source *1* of the exciting electromagnetic field with a step of 1 mm. The horn antenna *4* is positioned against the slot at a distance of 150 mm. The samples were mounted in the holder normal to the *x* axis and moved along this axis.

The unequally spaced linear antenna arrays with spatial excitation [32] were Golomb rulers of different orders (see Fig. 1,*b*, *3-1*–*3-5*) [17]. These Golomb rulers of the 1st to 4th orders had the largest distance between the edge elements in the array, with the lengths of 0, 1, 3, and 6 linear element sizes (abbreviated as l.e.s. here and below), respectively. The distances between the elements (in l.e.s.) used for the 4th-order ruler *3-5* were 1, 3, and 2. We also considered an unequally spaced linear antenna *3-6* with the distances of 2, 1, and 3 l.e.s., which is not a Golomb ruler, because the distances are equal between the first and third element, as well as between the third and fourth element. A linear oscillator was used as reference: it was a vertical rod antenna (see Fig. 1,*b*, *3-1*), composed of 6 elements, and a 24 × 24 mm copper shield.

The radiating element in the given arrays was a 4 × 4 × 4 mm cube; the linear oscillator was a rectangular parallelepiped of 24 × 4 × 4 mm, consisting of 6 radiating elements. The Golomb ruler arrays were also composed of such elements, depending on the order of the rulers (from 2nd to 4th). For example, the antenna that was a 4th order Golomb ruler of length 6 with the distances of 1, 3 and 2 was a linear structure composed of 4 elements, the distances between which were 4, 12 and 8 mm (1, 3 and 2 l.e.s., respectively).

The antenna that was a 1st order Golomb ruler with a length of 1 l.e.s. was a single radiating element.

The radiating elements in the AA were made of copper, pressed from an HTSC $YBa_2Cu_3O_{7-\delta}$ powder and from a nanopowder of the same composition (nanoHTSC).

Samples of HTSC powder with the 1-2-3 composition were prepared by the standard ceramic technology. NanoHTSC samples with the $YBa_2Cu_3O_{7-\delta}$ composition were prepared from a nanopowder synthesized by the glycine-nitrate method described in [19]. The advantage of the proposed synthesis method is that $YBa_2Cu_3O_{7-\delta}$ can be prepared as nanostructured powders with different particle size distributions, yielding high-temperature superconducting ceramics with several benefits:

samples are optimally saturated with oxygen;
samples have approximately the same density;
samples are ready in one sintering stage;
technique is not overly complicated and does not require high energy costs.
The elements included in the array were attached to a polystyrene foam strip with BF-2 glue.

Results and discussion

Fig. 2 shows the standing wave profiles measured at room temperature for a reference copper shield. If $x = 0$, the amplitude of the received signal is close to zero, which is in agreement with the data on the radiation pattern of the reflecting plane (normalized values of the measured signal amplitude are given).

The signal amplitude for a copper shield first increases sharply with an increase in the distance x from the source, and then generally decreases following a law weaker than $1/x$; in this case, amplitude oscillations with a period of 12–13 mm are observed.

This behavior of the amplitude contradicts the generally accepted assumption that the amplitude of the electromagnetic field drops sharply in the near field; however, this is in agreement with the dependence of the amplitude on the distance in the near field by a law weaker than $U \sim 1/x$, calculated in [20].

The oscillations observed in our experiment are explained by the interference of waves emitted by the antenna excitation source (feed) and the antenna itself at the location of the receiving device.

Fig. 3 shows a comparison of the measured standing wave profiles for a linear oscillator and Golomb rulers based on HTSC materials (at room temperature); amplitudes are normalized. The standing wave profiles of the copper-based Golomb rulers exhibit the same behaviors, except that the signal amplitude is about 1.5 times higher. The reason for this is that the resistance of copper ($1.7 \cdot 10^{-6}$ Ohm·cm) at room temperature is lower than that of the HTSC used, which is about $5 \cdot 10^{-5}$ Ohm·cm.

Analyzing Fig. 3, we can draw the following conclusions:

a pronounced interference pattern is observed for a solid rod antenna, similar to the pattern for a copper shield; however, no drop in the signal amplitude is observed with increasing distance;

the standing wave profile for Golomb arrays changes with increasing ruler order, the interference amplitude decreases, disappearing completely for the rulers of the 3rd and 4th orders under the given experimental conditions;

the interference pattern (albeit rather weak) persists for an unequally spaced rod antenna that is not a Golomb ruler;

interference dips are observed at $x = 0.12$–5 and 22–25 mm for all antennas; these dips appear during the interaction of waves propagating directly from the radiator to the horn and reflected from the samples (in the given experimental geometry).

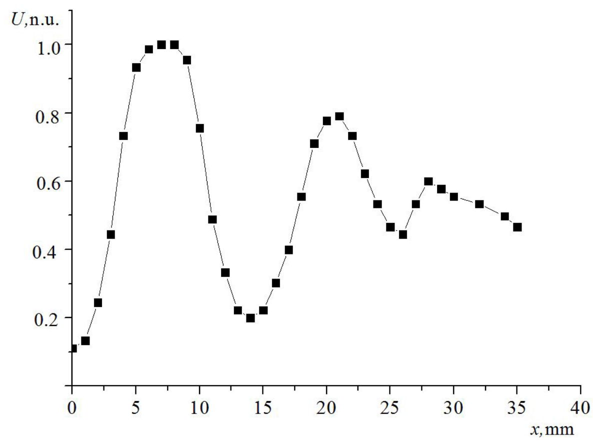

Fig. 2. Standing wave profile for copper shield at room temperature (experimental dependence of normalized signal amplitudes on the distance to the wave source)

If $x = 0$, the amplitude of the received signal is close to zero in all cases considered (the reflective shield, radiating element and Golomb rulers are made of copper and HTSC), which agrees with the data on the radiation pattern of the reflecting plane and the rod antenna.

No amplitude oscillations were observed for the received signal of the Golomb rulers of the 3rd and 4th orders (see Fig. 3), which can be explained by complex interference of the fields radiated by each of the antenna elements. The antenna elements are unequally spaced, and the distance between them is never the same, which is why a clear interference pattern cannot be detected. At the same time, an interference pattern is observed for an unequally spaced rod antenna that is not a Golomb ruler.

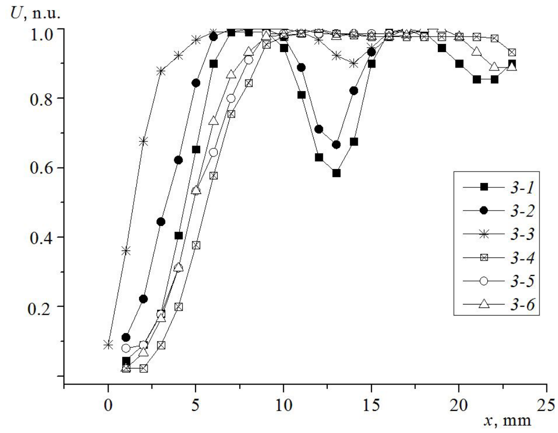

Fig. 3. Standing wave profiles for the samples considered (curve numbers correspond to element numbers in Fig. 1,*b*)

Calculation of the parameters of the radiation pattern for a complex antenna composed of cubes, with unequally spaced antenna elements, is challenging within our experimental conditions, remaining well beyond the scope of this paper.

Fig. 4 shows the experimental data on the temperature dependence of the standing wave profile of the antenna that were 4th-order Golomb rulers made of different materials. The results are similar for Golomb rulers of other orders.

The measurements were carried out for 4th-order Golomb rulers at the point located in the region with the greatest amplitude U of the received signal (for $x = 5$ mm). A slight increase in the intensity of the received signal is observed for a copper element with decreasing temperature, which is consistent with an increase in the conductivity of metals upon cooling.

The $U(T)$ dependence observed for an element made of a 1-2-3 HTSC powder is characteristic for such materials. As discussed above, the resistance of the HTSC used is higher at high temperatures above the superconducting transition point compared to copper; accordingly, the amplitude of the reflected signal is smaller. A rather sharp increase is observed upon cooling in the intensity of the received signal in the temperature range corresponding to the superconductivity transition of the HTSC (98–82 K) [21]. The level of the received signal is no longer temperature-dependent at temperatures below 82 K.

A similar dependence is observed for an element made of nanoHTSC powder, but there are certain nuances. The superconducting transition is stretched, and two regions are observed on the $U(T)$ curve near this transition: one in the range of 98–95 K and the other at temperatures below 80 K, which may be due to the two-phase structure in the sintered nanoHTSC powder [22]. The superconducting transition temperature of these ceramics is increased to about 96 K, which is apparently due to a decrease in the particle size (by about 20 times) compared with that for ceramics manufactured by the conventional technology.

An increase in the amplitude of the received signal by about 10 times is observed in our experiment during cooling and transition to the superconducting state. This is much less than the decrease in the resistance of the material during such a transition (by more than 10^5 times [23]).

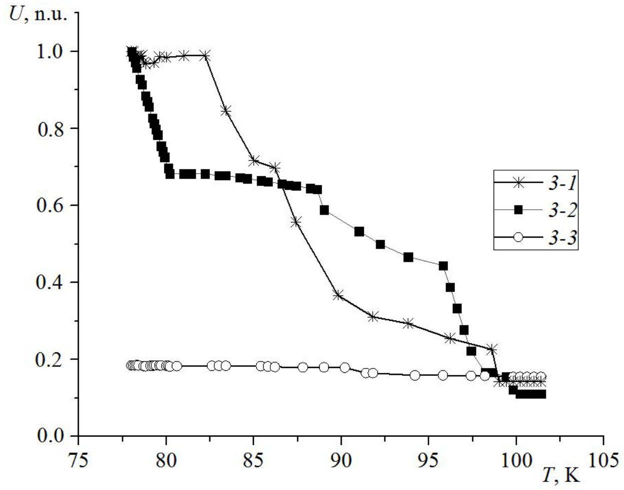

Fig. 4. Temperature dependences of received signal amplitude for 4th-order Golomb arrays made of standard 1-2-3 HTSC powder (*1*), nanoHTSC (*2*) and copper (*3*) in the superconducting transition range of the HTSC used (75–105 K)

This difference can be explained by the real experimental conditions: specifically, an organic binder was used to prepare the cube from a powder. The binder not only reduces the volume fraction of the superconducting phase, which is about 80% in the initial powder, but also envelops the grains of the superconducting powder, serving to decrease the sizes of coupled homogeneous superconducting regions. Furthermore, since we investigated the reflection of an electromagnetic wave, only the properties of a thin skin layer can be observed in the experiment; the thickness of this layer is zero for superconductivity conditions. In turn, the concentration of defects on the surface of the elements used is higher compared to the bulk, which means that the superconducting properties are deteriorated [24].

The resistance of the material in the superconducting state should be zero at low temperatures below 80 K, but this is only true for direct current. As for the microwave field used in the experiment, the resistance of the material is nonzero and depends on the frequency of electromagnetic oscillations. This is likely because charge carriers other than superconducting electrons are found in the material. These carriers are accelerated by the microwave field and dissipate energy in the form of Joule heat. Accordingly, the reflective properties are also deteriorated, and this is observed in the experiment.

Conclusion

This paper reports on the studies of amplitudes of electromagnetic waves (standing wave profile) depending on the arrangement of the reflective antenna arrays (Golomb rulers made of copper and HTSC structures) relative to the excitation source and the receiving device. We have considered antenna arrays based on Golomb rulers of the 1st, 2nd, 3rd and 4th orders and with the lengths of 0, 1, 3 and 6, consisting of cubes made from copper and pressed HTSC powders.

The antennas composed of cubes are rather complex, especially because the antenna elements are unequally spaced, so calculating the parameters of the radiation pattern for these antennas remains a challenge: clearly, further experiments are required in this direction.

The peculiarities of Golomb rulers, particularly those including superconducting elements, that we have uncovered show immense promise for applications in RF/microwave devices.

As no dips are observed in the standing wave patterns for the 3rd and 4th order Golomb rulers, and this is likely true for higher-order rulers as well, antennas with no signal failure in the near field and transition region can be reproduced for real-life operation. Golomb arrays therefore offer undoubted benefits for manufacturing antennas that can maintain a constant signal amplitude in the near field.

Both the absence of dips on the amplitude profile of the standing wave for a 4th-order Golomb ruler, and the simultaneous presence of such dips on the corresponding profile for an unequally spaced rod antenna (which is not a Golomb ruler but has the same length and the same number of elements) and on the profiles for lower-order Golomb rulers should allow to control the reflective properties of antennas by shifting and switching the antenna elements.

Including superconducting elements into the scheme will not only increase the efficiency of the antenna but also make it possible to manipulate its characteristics by selecting the temperature regime, and therefore the resistances of the constituent elements and their reflective properties.

Such properties are particularly important for novel materials with superconductivity at room temperature [25, 26].

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THE AUTHORS

FARADZHEVA Mislimat P.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
faradzheva_mp@spbstu.ru
ORCID: 0000-0001-9754-3965

PRIKHOD'KO Aleksandr V.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
aleks@physics.spbstu.ru
ORCID: 0000-0002-9015-4251

KON'KOV Oleg I.
Ioffe Institute of the Russian Academy of Sciences
26, Polytekhnicheskaya St., St. Petersburg, 194021, Russia
oleg-l705@yandex.ru
ORCID: 0000-0002-2223-1067

СВЕДЕНИЯ ОБ АВТОРАХ

ФАРАДЖЕВА Мислимат Пиралиевна – *кандидат технических наук, доцент кафедры физики Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
faradzheva_mp@spbstu.ru
ORCID: 0000-0001-9754-3965

ПРИХОДЬКО Александр Владимирович – *доктор физико-математических наук, профессор кафедры физики Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
aleks@physics.spbstu.ru
ORCID: 0000-0002-9015-4251

КОНЬКОВ Олег Игоревич – *кандидат физико-математических наук, старший научный сотрудник Физико-технического института им. А. Ф. Иоффе РАН.*
194021, Россия, г. Санкт-Петербург, Политехническая ул., 26
oleg-l705@yandex.ru
ORCID: 0000-0002-2223-1067

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