Quantum phase with no translational symmetry and its potentiality for quantum communication

S. A. Emelyanov

Division of Solid State Electronics, Ioffe Institute, St. Petersburg, Russia

By the method of terahertz photo-voltaic spectroscopy we have found a quantum phase that possesses neither continuous nor discrete translational symmetry. The phase is originated from quantum Hall state under nonzero toroidal moment. In the phase, we have observed the effect of a distant response to a local laser excitation. We provide strong evidence that the effect is the implementation of a *purely* quantum communication, which is unrelated to quantum entanglement and based *solely* on instantaneous collapse of electron wavefunction under interaction.

PACS: 73.50.Pz, 73.43.Nq, 05.65.+b, 03.67.Hk

I. INTRODUCTION

To date, no states of matter are known, in which both continuous and discrete translational symmetry completely disappear. Intuitively, this fact seems quite natural because it is truly hard to imagine a fully self-ordered macroscopic system in such a way that any system's domain of an arbitrary size has "its own face" with respect to the other domains of that size.

However, a hint at the quantum phase of that kind may be found in the solution of the Schrödinger equation for infinite 2D systems that possess so-called toroidal moment $\vec{T}$ [1-2]. Following to [3], for a single quantum well in presence of tilted quantizing magnetic field ($\vec{B}$), this moment can be written as $\vec{T} \propto \vec{B} \times \vec{E}$, where $\vec{E}$ is the so-called "built-in" electric field related to an asymmetry of confining potential. In contrast to familiar integral quantum Hall (IQH) solution, here the Landau level degeneracy may be lifted ($v_y(k_y) = \frac{1}{\hbar}\frac{\partial \varepsilon}{\partial k_y} \neq 0$) and energy spectrum is asymmetric in k-space ($\varepsilon(k_y) \neq \varepsilon(-k_y)$), where *Y*-direction is perpendicular to both the in-plane component of magnetic field (*X*) and the growth direction (*Z*). The electrons are thus delocalized in the *Y*-direction but spatially-separated in the *X*-direction in accordance with the following relation: $x_0 = -k_y r^2$, where x_0 is their *X*-coordinate and r is the magnetic length. Actually, this relation is known also in conventional IQH systems [4] but the difference is that now the electrons' directed velocities (v_y) may be nonzero. As a result, we obtain a set of spatially-separated one-dimensional counter-flowing spontaneous currents in the *Y*-direction with no spatial periodicity in the *X*-direction. Moreover, the electrons are thus spatially self-ordered in the *X*-direction: v_y is in a one-to-one correspondence with k_y and hence with x_0.

The problem with this solution is that it cannot actually be applied to any real system in its present form because one-dimensional spontaneous currents clearly cannot exist in any object of a finite size. Taking also into account that no signature of lifting of Landau level degeneracy has been observed in various magneto-transport and optical experiments, the relevance of this solution to the reality is thus an open question.

In this work, we take an original approach to the problem. The approach is based on the study of high-speed light-induced in-plane currents in unbiased IQH system with nonzero toroidal moment. Phenomenologically, these currents are a manifestation of so-called photo-voltaic (PV) effect [5], which may occur in unbiased 2D systems that possess an in-plane asymmetry.

II. EXPERIMENTAL DETAILS

Our radiation source is a terahertz pulsed gas laser optically pumped by tunable high-pressure CO_2 laser [6]. The active medium is ammonia (NH_3). The wavelength is 90.6 μm ($\hbar\omega = 13.7$meV), pulse duration is 40ns, and intensity of incident radiation is about 200W/cm^2. Fig. 1 shows typical laser track monitored by a high-speed photon-drag detector. In most experiments we use linearly polarized laser radiation incident normally onto sample surface.

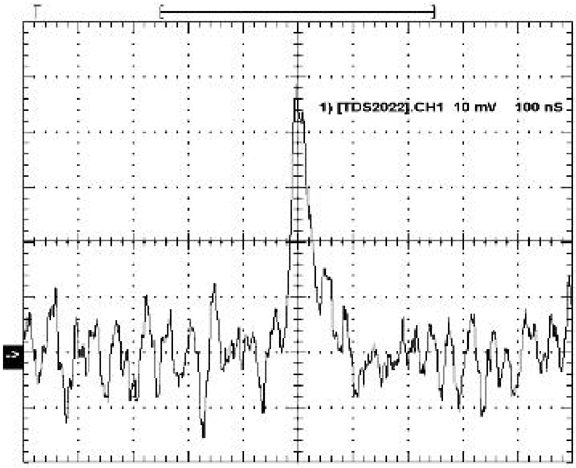

Fig. 1. Typical track of ammonia laser. Timescale is 100ns/div.

The structures are not-intentionally doped InAs-AlGaSb single quantum wells grown by molecular beam epitaxy (MBE). Taking into account that the GaSb valance band is overlap the conduction band of InAs by about 100 meV, a 15-nm-wide conducting layer of InAs is sandwiched between two 10-nm-wide AlSb barriers to avoid any hybridization-related effects. The structures consist thus of a thick GaSb buffer layer followed by this sandwich with a 20-nm-wide GaSb capping layer. A typical value of the low-temperature electron sheet density and of the mobility is $1.4 \cdot 10^{12}\,\mathrm{cm}^{-2}$ and $10^5\,\mathrm{cm}^2/\mathrm{Vs}$, respectively. The experiments are performed at $T = 1.9\,\mathrm{K}$ in a short-circuit regime with 50Ω load resistor. As a rule, the external magnetic field (up to 6.5T) is tilted at an angle of about 15° with respect to the normal to provide nonzero toroidal moment.

Since the presence of built-in electric field is crucial, prior to the main experiments all samples are tested by the method shown in the inset of Fig. 2. The testing is based on the fact that an in-plane magnetic field alone, as a pseudo-vector, can not be the reason for an in-plane PV response, which is a polar vector. However, a cross product of in-plane magnetic field and built-in electric field does provide in-plane polar vector that is just the toroidal moment. In this case, a PV response could occur. Fig. 2 shows typical outcome of the testing. It is seen that a non-resonant PV response does occur and increase with increasing of magnetic field. Hence, built-in electric field does exist in our structures.

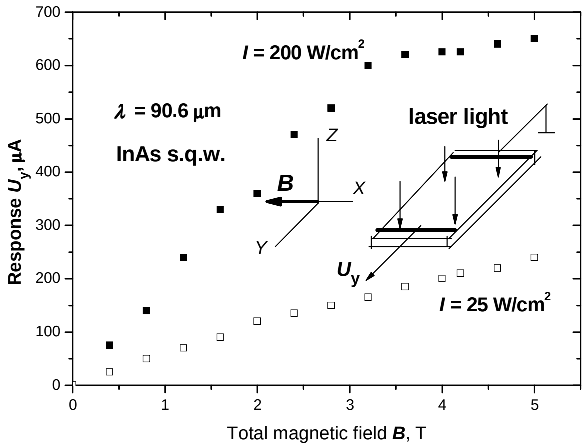

Fig. 2. PV response as a function of in-plane magnetic field for two terahertz laser intensities. The inset shows experimental geometry.

Rough estimation of built-in field by the method of Ref. [7] yields the average value of about $4 \cdot 10^4$ V/cm. It should be noted, however, that the true potential profile is rather exponential than linear because of the high electron density in our structures. Therefore, a local value of built-in field may be much higher, especially in the close vicinity of a more charged interface. As a result, the effects that require higher built-in fields could exist but most likely with an effective electron density lower than the total density.

III. RESULTS AND DISCUSSION

A. Evidence for current-carrying states under IQH conditions

As the quantizing component of magnetic field appears in the geometry in Fig. 2, the non-resonant PV response quickly disappears due to the Landau quantization. At the tilting angle of about 15°, this response occurs only below 2T (Fig. 3). However, as it is seen from this figure, a prominent resonant response surprisingly emerges. The response reverses with reverse of B_x but is insensitive to the rotation of the direction of light polarization in the well plane.

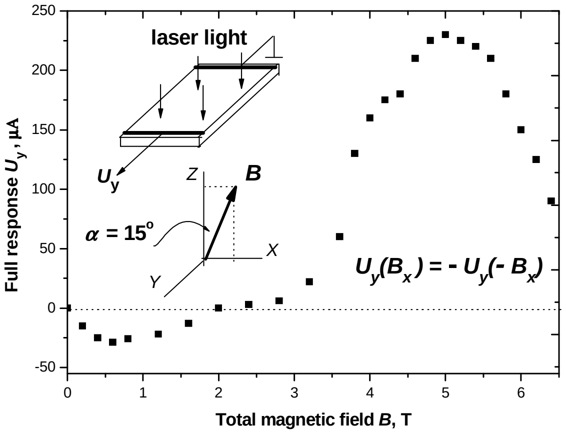

Fig. 3. PV response in the *Y*-direction as a function of magnetic field tilted in the *XZ* plane. The inset shows experimental geometry.

The peak position ($B \approx 5\,\mathrm{T}$) indicates the relevance of the cyclotron resonance (CR). However, the so high PV response under the strong Landau quantization is a puzzle indeed because it implies the presence of quantum states, in which electrons are capable to provide a detectable current with *no* electric bias. Such current-carrying (CC) states should not exist in an ideal IQH system. The also important fact is CR in PV spectra is much wider than CR in optical transmission spectra (see, e.g., [8]) though, in contrast to the later, the former show no a saturation behaviour. Moreover, experiments with a circularly polarized light have shown that CR in the PV spectra is practically insensitive to the light polarization though CR in transmission spectra occurs only under cyclotron-resonance-active polarization. All these facts show that CR in PV spectra and CR in transmission spectra are of a different origin: the former should be related to peculiar CC states while the later is related to conventional IQH states. The density of the IQH states is most likely much higher than that of the CC states because the former contribute only to transmission spectra while the later contribute to both transmission and PV spectra. One of the possible reasons is just an exponential profile of the built-in field. On the other hand, as it follows from the wider PV spectra, the CC states are more smeared around the Landau levels than the IQH states.

B. Evidence for translational symmetry breaking caused by CC states

To clarify the origin of the CC states we perform the experiment shown in the inset of Fig. 4. We measure local PV spectra in a large sample ($19\times12\,\mathrm{mm}^2$) with equidistant short contact pairs, which are simply a translation (in the *X*-direction) of a single pair in increments of 2mm. The length of each contact is 1mm. To avoid edging effects they all are remote from the closest border by 0.5mm. For convenience, the pairs are numbered from left to right.

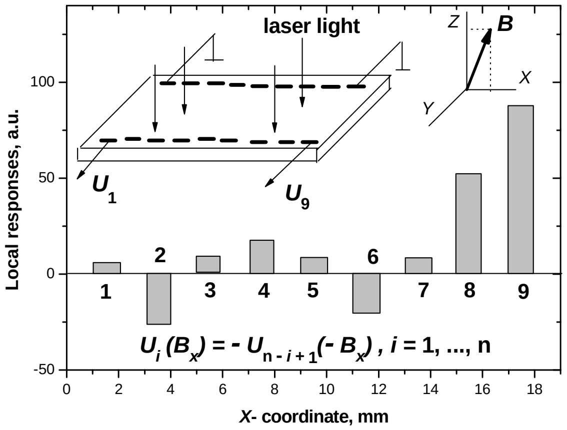

Fig. 4. Spatial distribution of local *y*-responses throughout the sample in the *X*-direction at $B = 5$ T. Each response is shown via a rectangle of a proper height and polarity. Experimental conditions are the same as in Fig.3. The relation at the figure bottom shows roughly a redistribution of the responses under switching of in-plane magnetic field.

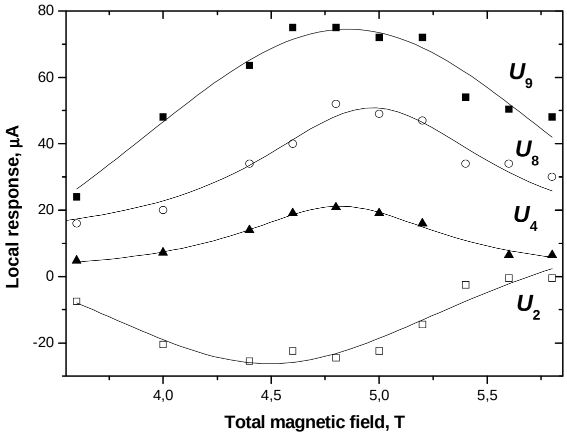

Fig. 5. Local PV spectra for four selected contact pairs ($i = 2$; 4; 8; 9) in the experiment of Fig. 4. Solid lines are a guide for the eye.

At first sight, the outcome of this experiment seems quite predictable: local responses should be practically the same because the spatial homogeneity of the sample in the *XY*-plane was carefully tested before the experiment. However, the true outcome is quite unexpected (Fig. 4). At a fixed magnetic field ($B = 5\,\mathrm{T}$) local responses are a non-monotonic alternative-sign function of the *X*-coordinate. Moreover, CR peak position is also a function of the *X*-coordinate (Fig. 5). Reversed B_x results in a quite non-chaotic spatial redistribution of local responses roughly in accordance with the following empiric relation: $U_i(B_x) = -U_{n-i+1}(-B_x)$, where n is the total number of pairs. This means local responses cannot be assigned to a certain sample's domain and hence local defects are of a minor importance. In fact, the non-chaotic spatial redistribution of the responses implies that the CC states are spatially-separated in the *X*-direction and moreover somehow ordered with no spatial periodicity in this direction. The ordering is thus governed by B_x as well as by the sample size.

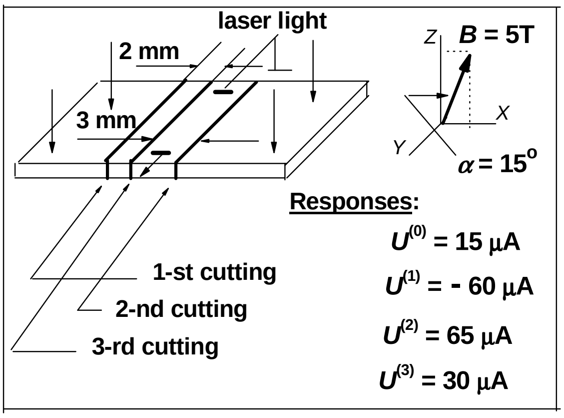

Fig. 6. Experimental demonstration of high sensitivity of a local PV response to the sample length in the *X*-direction.

However, if such ordering does exist, then a local response should be very sensitive to the distances to both sample edges *independently* of their remoteness. To examine this point we perform a qualitative experiment shown Fig. 6. Once again, we use a large sample ($19\times12\,\mathrm{mm}^2$) but with a single contact pair centered in the *X*-direction. We measure PV response at this pair each time the sample has become shorter because of a mechanical cutting. The response after each cutting is shown in the right-hand corner of the figure, where upper index indicates the number of cuttings before the measurement. It is clearly seen that each cutting does change drastically the response despite the fact that each new sample edge is remote from the contact pair on a macroscopic distance.

C. Characterization of CC states

To further characterize the CC states we measure PV responses in the *X*-direction just like we have done in the *Y*-direction. Fig. 7 shows the same experiment as in Fig. 3 but magnetic field is rotated by 90° about *Z*-axis (see inset of Fig. 7). It is seen that resonant respose occurs in the *X*-direction as well as in the *Y*-direction. Moreover, both spectra look like quite identical and the only difference is that the former is even in magnetic field while the later is odd. Such an identity indicates that the responses in *X*- and *Y*-direction are most likely a counterpart of each other and a spatial ordering of electrons should exist in the *Y*-direction as well.

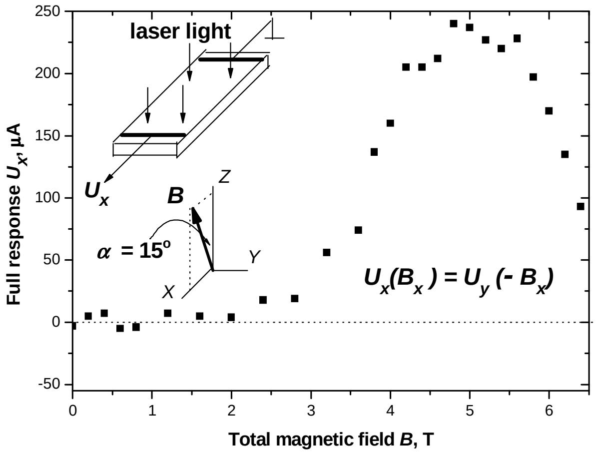

Fig. 7. PV response in the *X*-direction as a function of magnetic field. Experimental conditions as well as the sample are the same as in Fig. 3.

To be sure of that, we perform the experiment shown in Fig. 8, which is reminiscent that one in Fig. 4 but now we measure local *x*-responses instead of local *y*-responses (see inset of Fig 8). As expected, local *x*-responses are a strong function of coordinate (now *Y*-coordinate) though the details of their spatial distribution differ from that in Fig. 4. This observation justifies that the CC states are spatially-separated (and somehow ordered) in the *Y*-direction as well as in the *X*-direction.

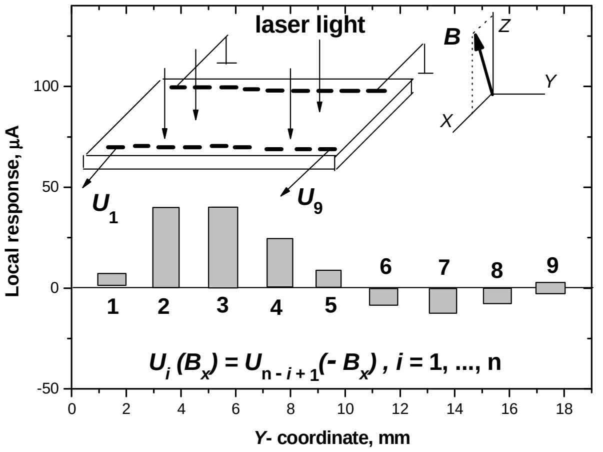

Fig. 8. Spatial distribution of local *x*-responses throughout the sample in the *Y*-direction at $B = 5$ T. Experimental conditions are the same as in Fig. 4 but magnetic field is rotated by 90° about *Z*-axis. The relation at the figure bottom shows roughly a redistribution of the responses under switching of in-plane magnetic field.

In general, our observations may thus be interpreted in terms of a peculiar quantum phase that emerges from the IQH state through a continuous phase transition associated with toroidal moment. The transition is accompanied by the breaking of translational symmetry, which is caused by the CC states. These states are spatially separated and somehow ordered with no spatial periodicity in both *X*- and *Y*-directions. Moreover, they are capable to provide in-plane ohmic currents in both directions under spatially-homogeneous photo-excitation. Taking into account all these characteristic features of the CC states, one can conclude that they should be something like two-dimensional electron orbits (or quantum circuits), at which the electrons flow in a certain direction, and moreover these orbits should be more or less macroscopic. In this case, light-induced ohmic current could emerge if, for a resonant optical transition, the final orbit in upper Landau level and the initial orbit in lower level (i.e. “hole”) are not exactly the same. This current should thus be sensitive to the spatial distribution of the orbits and hence should be a non-monotonic function of coordinates.

However, if the concept is valid, then both the direction and the absolute value of a local response may be a complicate function of even the distance between the short contacts. To examine this point we perform the experiment shown in the inset of Fig. 9. It is organized as follows. Initially, we take the sample with a single short contact pair (*a* and *b*) and measure PV spectrum at this pair (U_{a-b}). Then, we add a one more contact (*c*) between the former ones and measure two more spectra (U_{a-c} and U_{c-b}). Fig. 9 shows all spectra. It is seen that, in accordance with our expectations, the spectra are strongly non-additive indeed ($U_{a-b} \neq U_{a-c} + U_{c-b}$) and even their CR peak position is not the same.

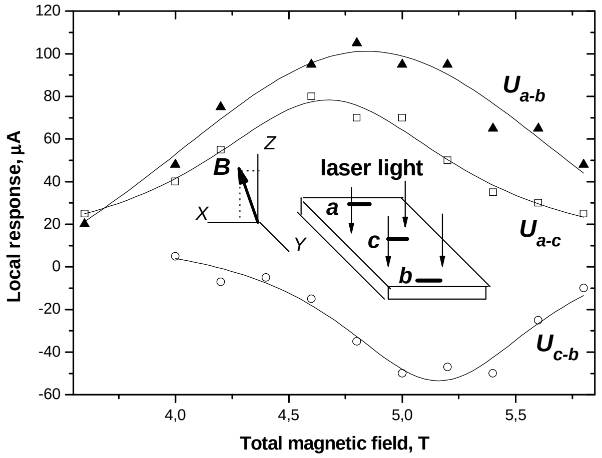

Fig. 9. Experiment with adding of a new contact. Sample size is 5 × 12mm^2. All contacts are 1-mm-long and centered in the *X*-direction. The details of the experiment are in the text. Solid lines are a guide for the eye.

Although our concept does not still describe the origin of the long-range electron orbits, even now we can rule out the interpretation in terms of so-called incompressible islands [9-10] as well as in terms of a stripe phase that could potentially occur in a quantum Hall system [11]. The point is the incompressible islands should disappear under intense resonant excitation (optical breakdown) while any stripe phases require much lower temperature and higher mobility. Moreover, spatial distribution of both incompressible islands and stripes should be more or less uniform and anyway should not be so sensitive to the switching of in-plane magnetic field.

D. Direct evidence for electron orbits of a centimetre scale

The true extraordinary point of proposed concept is just a macroscopic lengthscale of the electron orbits at the CC states because no physical systems with the quantum states of that kind are known yet. However, if the concept is nonetheless valid, then we are getting such opportunities that have so far been only a subject of dreams. The most exciting one is that we can easily excite an electron in a certain spatial region but detect this electron in another spatial region though these regions can be remote from each other on a macroscopic distance (Fig. 10). Of course, such experiment is impossible at atomic scale. As for our experiments, if the lengthscale of electron orbits are truly of the order of sample size, then, in accordance with the fundamentals of quantum mechanics, one would expect the following striking effect: local PV responses should be detected throughout the *whole* sample even if we illuminate only a *part* of it. Moreover, a reduction of illuminated area should result in approximately the *same* relative reduction of *all* responses independently of whether or not they are in the spotlit region.

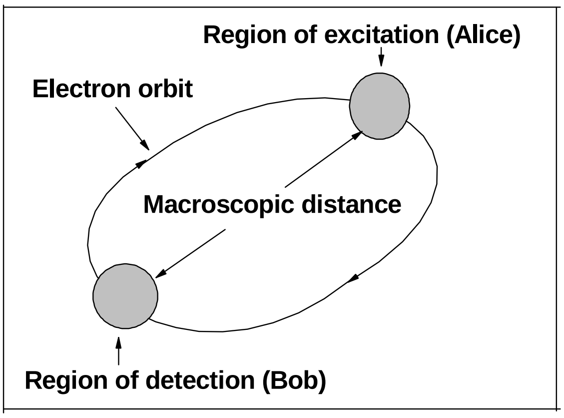

Fig. 10. Potential experiment, if macroscopic-range electron orbits do exist.

Thus, the final experiment to examine our concept is shown in the inset of Fig. 11. Here the conditions are the same as in Fig. 4 but the difference is that now we illuminate only about one third of the sample (pair No. 3 and downwards) while the residual part (pair No. 4 and upwards) is covered by a non-transparent mask. To be honest, the outcome of this experiment exceeds even the most optimistic expectations (Fig. 11). It is clearly seen that PV responses do occur far beyond the laser spot so that the *highest* response can be detected at the contacts that are *farthest* from the spot and the distance between them is as long as about 1cm. Moreover, through the comparison of the experiments in Figs. 4 and 11, one can see that this effect is a direct consequence of a more general one: reduction of illuminated area results in approximately the same relative reduction of all local responses independently of whether or not they are in the spotlit region. That is exactly what we need. Following to our concept, this means a lot of electron orbits cross the spotlit region, i.e. a lot of them are as long as about 1cm. Furthermore, qualitatively the same effect has been observed for the *x*-responses when a part of the sample is covered by a non-transparent mask in the geometry of Fig. 8. This means the characteristic length of the orbits is roughly the same in both *X*- and *Y*-directions.

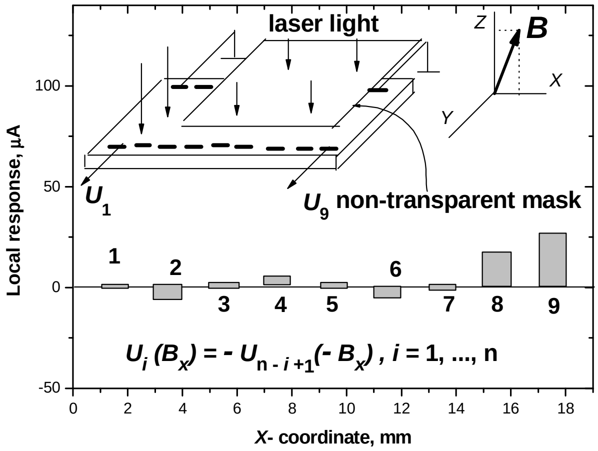

Fig. 11. The same experiment as in Fig. 4 but about two thirds of the sample (pair No. 4 and upwards) are covered by a non-transparent mask. The relation at the figure bottom shows roughly a redistribution of the responses under switching of in-plane magnetic field.

One of the most stunning points of our concept is that *all* local responses should appear *synchronously* even if a part of them is far beyond the laser spot. The characteristic time of the appearance of all responses should thus be the same and is of the order of the electron lifetime known to be about 10ps for the structures used [14]. To examine this point, we detect synchronously the response from pair No.2 (spotlit region) and the response from pair No.9 (unlit region). It is seen from Fig. 12 that, in accordance with the concept, no delay between these signals is observed at least within an accuracy of about 30ns.

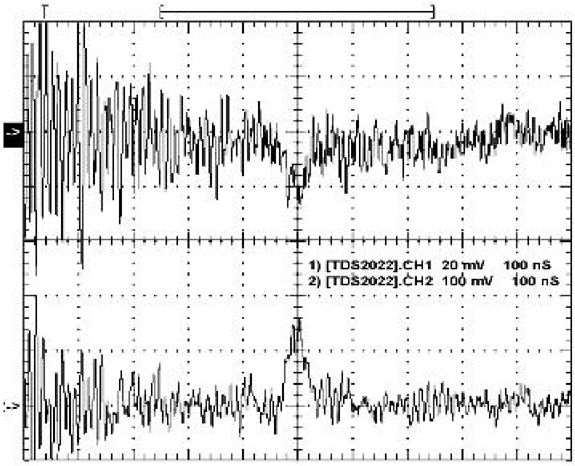

Fig. 12. Synchronously-detected local responses in the experiment of Fig. 10. Upper track is the response from pair No. 2; lower track – from pair No. 9. Timescale is 100 ns/div. Both signals are pre-amplified with the gain factor of about 100.

However, may be one would propose an alternative interpretation of the last experiment? To answer this question it should be noted that generally speaking only a few physical systems are known, in which a maximal photo-response may occur on a macroscopic distance from laser spot. We mean the system of cold excitons in coupled quantum wells [12] and the Bose-Einstein condensate of an ultra-cold gas [13]. In both cases, however, the effect is caused by the transport of some long-living excitations beyond the laser spot with a subsequent decay. This model is clearly irrelevant to our system simply because there are no such long-living excitations. Indeed, from the last experiment one can easily *underestimate* the speed of these imaginary excitations. Their speed should be higher than $3\cdot10^7$ cm/s while their mean free path should be *longer than 1cm*. This is absolutely incredible for our dense medium. Moreover, any transport model definitely cannot explain many other facts. For example, (1) the length of the unlit region strongly affects spatial distribution of local responses in the spotlit domain and (2) the “space jump” of the highest response from unlit (pair No. 9) to spotlit (pair No. 1) region with the switching of in-plane magnetic field (see empiric relation at the bottom of Fig. 11).

E. Quantum communication with no entangled states

Now it has become clear that *de facto* the last experiment is the implementation of an original scheme of quantum communication, which is unrelated to quantum entanglement and is based *solely* on such a fundamental thing as instantaneous collapse of electron wavefunction under interaction. Using commonly accepted terminology, through the laser excitation of our sample Alice can send Bob real information and Bob can easily “read” it through the measurement of a local PV response beyond the laser spot (see Fig. 10). In the experiment of Fig. 11 the distance between Alice and Bob is about 1cm, if Bob measure the response, say, at the contacts No. 9. Taking into account the characteristic time of Bob’s measurements, one can come to a shocking conclusion that perhaps superluminal communication is *already implemented* in our experiment. Moreover, in the context of the implementation of superluminal communication we have the following additional resources. (1) The distance between Alice and Bob may potentially be as long as one likes because, as it follows from our experiment, the lengthscale of the electron orbits depends only on the sample size. (2) The sample may potentially be prepared in such a way that the electron lifetime will be shorter than 10ps to minimize the characteristic time of Bob’s measurements. Utilization of both resources is rather a technological problem and has no apparent limitations of a fundamental character. Note also that the intensity of laser excitation is also practically unlimited so that one can easily provide a high enough number of electrons at the excited states during the time shorter than the electron lifetime.

Of course, as an immediate objection, one would recall the familiar no-communication theorem. However, under a closer consideration, it is easy to see that the proposed communication scheme is not a subject to this theorem. The theorem states that no communication can be achieved via a shared *entangled* state. However, a distinct feature of this scheme is just the unimportance of entanglement. As a result, Bob needs neither a detection of individual entangled particles nor a decoding of the signals received.

Finally, it should be noted that in the context of superluminal communication, a higher temporal resolution in Fig. 12 is a more optimal. Ideally, it should be of the order of 0.1ns that is just the characteristic time to overcome the distance of about 1cm with the speed of light. Such an experiment seems quite real, especially if the laser pulse is also shortened to 0.1ns.

IV. SUMMARY

By the method of terahertz photovoltaic resonant spectroscopy we provide strong evidence for a quantum phase with no either continuous or discrete translational symmetry. The phase emerges in a quantum Hall system when its toroidal moment has become nonzero. We have demonstrated that the symmetry breaking is associated with the quantum states, which are quantum orbits of a centimetre lengthscale. In the phase, we have observed the effect of a distant system's response to a local laser excitation. We provide strong evidence that the effect is the implementation of a peculiar quantum communication, which is unrelated to quantum entanglement and does not thus contradict the no-communication theorem.

ACKNOWLEDGMENTS

The MBE samples were kindly provided by B. Y. Meltser and S. V. Ivanov (Center of Nanoheterostructure Physics, Ioffe Institute).

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