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Why quantum engineering?

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The progress in experimental techniques and theoretical modeling made possible to fabricate and test macroscopic structures, which use quantum coherent solid state qubits as building blocks. The results of such quantum engineering are likely to go far beyond the limited goals of quantum computing and quantum communication and provide a direct way to probing quantum-classical boundary. Some recent developments are discussed.

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78.67.Pt Multilayers; superlattices; photonic structures; metamaterials;
03.67.–a Quantum information.

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It is always risky to combine well-known and well-tested notions in order to describe something new, since in the future these combinations are likely to be abused. After «quantum leaps» were appropriated by the public at large, nobody except physicists and some chemists seems to realize that they are exceedingly small, and that breathless descriptions of quantum leaps in policy, economy, engineering and human progress in general may actually provide an accurate, if sarcastic, picture of the reality. When the notion of the «marketplace of ideas» was embraced by the academia, scientists failed to recognize that among other things this means spending 95% of your resources on marketing instead of research.* Nevertheless «quantum engineering» seems a justified and necessary name for the fast expanding field, which, in spite of their close relations and common origins, is quite distinct from both «nanotechnology» and «quantum computing» in scope, approaches and purposes.

The miniaturization of electronic devices to the point where quantum effects must be taken into account produced much of the momentum behind nanotechnology, together with the need to better understand and control matter on the molecular level coming from, e.g., the molecular biology and biochemistry (see, e.g., Ref. 3 (Ch. 1)). One also often uses the term «mesoscopic physics», especially with respect to solid state devices, meaning the objects on the intermediate scale between truly microscopic (single atoms or small molecules) and truly macroscopic. Despite their comparatively large size ($\sim 10^{11}$–10^{12} particles), mesoscopic systems maintain enough quantum coherence for making quantum effects really matter (e.g., Ref. 4 (Ch. 1)). The experimental techniques and theoretical understanding developed in these fields strongly contributed to the development of quantum engineering.

Another, very strong, push was delivered by quantum computing. After the original papers [5–7] indicated the direction, i.e., the *essential* use of quantum properties of a system for computation, and the discoveries of Shor [8], Ekert and Josza [9], and Grover [10,11] algorithms brought the promise of a qualitative change in the computing capabilities, the field immediately became the focus of enormous amount of attention and funding, which produced some spectacular results on the proof-of-principle level.**

The physical side of the research on quantum computing is guided by the DiVincenzo's criteria [12,13]:

1. A scalable physical system with well characterized qubits.
2. The ability to initialize the state of the qubits to a simple fiducial state, such as $|000...\rangle$.
3. Long relevant decoherence times, much longer than the gate operation time.

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* See, e.g., Refs. 1 and 2.

** In the related field of quantum communications, including quantum key distribution, the requirements are intrinsically much less stringent and allow a direct use of optical technologies. As a result, devices for quantum communications are already commercially available from several companies.

4. A «universal» set of quantum gates.

5. A qubit-specific measurement capability.

The scalability here comes first for a reason: it is the hardest property to achieve in conjunction with the requirement for long enough global decoherence time. Solid state based devices were natural candidates from this point of view, despite the uncomfortably high number of degrees of freedom in both the qubits and the surroundings, which threatened to make quantum coherence times in the system uselessly short. Moreover, this large number of degrees of freedom made such devices suspect, since their operation as qubits would require to regularly produce «Schrödinger cat»-superposition of macroscopic quantum states, an admittedly hard task for even a single experiment [14]. Superconducting devices and quantum dots gave some of the best promise of scalability while holding the disruption of quantum coherence to an acceptable minimum and satisfying the rest of DiVincenzo criteria. The results [15–22] justified the expectations that quantum coherence can be preserved in these structures after all and made the kind of experiments hoped for in Ref. 14 almost routine. On the other side, the realization of a «standard» — gate-by-gate — quantum algorithm would require quantum error correction, necessary to extend the effective operation time of the quantum computer beyond the coherence time of a single qubit, at a price of a very large overhead in terms of both number of extra operations and extra physical qubits (see, e.g., Ref. 23). One of the alternative approaches, adiabatic quantum computing (AQC) [24–26], in a sense, swaps space for time, replacing the performance of unitary operations on separate qubits by creating an appropriate set of hard-wired interqubit couplings. Then the system is pushed into its ground state by applying a strong «external field»; adiabatic lifting of this field with high probability leaves the system in the ground state, which encodes the solution we are after. Being in the ground state automatically protects the system against decoherence [27]. With certain caveats, an adiabatic quantum computer is capable of solving any problem a «conventional» quantum computer can solve [28,29]. It is also expected that for certain problems an approximate adiabatic quantum computing (AAQC) approach — with weaker requirements than AQC — can find an approximate solution either exponentially faster, or with exponentially better precision, than a classical annealing algorithm would [30]. The experimental realization of either AQC or AAQC in superconducting qubits is not achieved yet [31], but it is expected that practically interesting results would require a rather large, but feasible, number of physical qubits, about several hundred.* Be as it may, the development of quantum computing already led to the development of reliable, scalable, solid state based — primarily superconducting — qubits, the physics and technology of which is now well understood (due in large part to the previous progress in mesoscopic physics), and means of efficiently connecting them to each other [33–37]. Now it brought to the forefront of research the theoretical analysis, design, fabrication and testing of large arrays of solid state based qubits operating coherently.

Meanwhile the need to test the limits of quantum mechanics through realizing truly macroscopic «Schrödinger cat» states, which was being consistently stressed [38,39] found special reasons for optimism in the successful developments in the field in superconducting qubits. The operation of such devices on large enough scale would either confirm or refute the applicability of quantum mechanics to arbitarily large systems, with fundamental consequences for science. Therefore putting more and more qubits together while maintaining their quantum coherence is a worthwile task also from the most fundamental point of view. Whether a working code-cracking or database-searching quantum computer is actually built in the process, would be, of course, a minor corollary to such a momentous development.

All these developments indicate that «quantum engineering» is emerging as a distinct branch of science and technology, which comprises theory, design and fabrication of large systems of interacting qubits, and their collective manipulation in quantum regime. Unlike nanotechnology, it is not limited by scale, but is also more focused on the single main type of unit building blocks — solid state based qubits — and on the essentially quantum properties of the resulting object. Unlike quantum computing, it is not restricted by the goal of algorithm implementation, and makes the emphasis on the properties of the structure on the large scale, as an effective medium. One question it is attempting to answer is, what interesting, specifically quantum-mechanical effects can be obtained using as many of the existing qubits as possible? The other, maybe more important, question is, what is the largest quantum coherent system one can make without running into some fundamental barrier?

The systems dealt with by quantum engineering must satisfy only a weakened set of criteria compared to DiVincenzo's: requirements (2) and (5) should extend only to *some* qubits, while (4) is not necessary. As an example, let us consider an electromagnetic wave propagating through a chain of identical qubits placed in a transmission line, Fig. 1, and considered as an effective medium [40,41]. For its analysis it is convenient to use the circuit

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[*] Regrettably, the publicly accessible data on recent ambitious attempts to realize AAQC and AQC in superconducting multiqubit structures do not allow to conclude whether the results were due to quantum adiabatic evolution, classical annealing, or some combination of both [32].

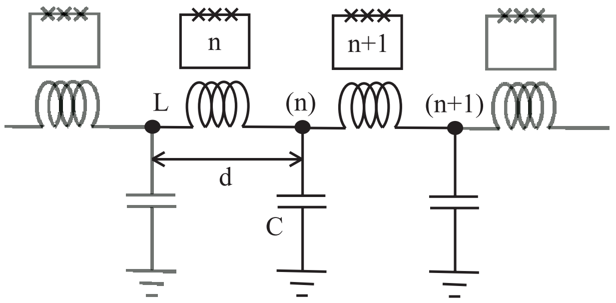

Fig. 1. Lumped element circuit for the simplest 1D quantum metamaterial — a chain of flux qubits with period d in a transmission line (after Ref. 40).

formalism [42], where each node is assigned a «flux» Φ_n, the time derivative of which is related to the node potential (in CGS units) via

$$\dot{\Phi}_n(t) = cV_n(t). \qquad (1)$$

The classical Lagrangian of the problem is

$$\mathcal{L}(\Psi,\Phi;\dot{\Psi},\dot{\Phi}) =$$

$$= \sum_n \left(C\frac{(\dot{\Phi}_n)^2}{2c^2} - \frac{(\Phi_n - \Phi_{n-1} - \tilde{\Psi}_n)^2}{2L} + \mathcal{L}_{n,qb}(\Psi,\dot{\Psi}) \right), \quad (2)$$

where $\mathcal{L}_{n,qb}$ describes the nth flux qubit, and $\tilde{\Psi}_n$ is the magnetic flux it induces in the corresponding loop. It is convenient to introduce the Routh function with respect to the qubit variables $\Psi, \dot{\Psi}$ by a partial Lagrange transformation:

$$\mathcal{R}(\Pi_\Psi,\Psi;\Phi,\dot{\Phi}) = \sum_a \Pi_{\Psi_a}\dot{\Psi}_a - \mathcal{L}(\Psi,\Phi;\dot{\Psi},\dot{\Phi}) \qquad (3)$$

(here $\Pi_\Psi = \partial_{\dot{\Psi}}\mathcal{L}$). The Routh function («Routhian») satisfies the Lagrange equations for the $(\Phi,\dot{\Phi})$-variables, and the Hamilton equations for the (Ψ,Π_Ψ)-ones:

$$\frac{d}{dt}\frac{\partial\mathcal{R}}{\partial\dot{\Phi}_n} - \frac{\partial\mathcal{R}}{\partial\Phi_n} = 0; \quad \frac{d}{dt}\Pi_{\Psi_n} = -\frac{\partial\mathcal{R}}{\partial\Psi_n}; \quad \frac{d}{dt}\Psi_n = \frac{\partial\mathcal{R}}{\partial\Pi_{\Psi_n}}, \qquad (4)$$

providing a convenient way of quantizing the qubits' degrees of freedom, while keeping the variables describing the transmission line classical. This corresponds to the quasiclassical treatment of light scattering by atoms (see, e.g., Ref. 45). The resulting equations of motion for the field in the line are in the continuum limit [40]

$$\ddot{\Phi}(x,t) - s^2\partial^2_{xx}\Phi(x,t) = s\Omega\Psi_0\,\partial_x\Lambda(x,t), \qquad (5)$$

where $\Omega = c/\sqrt{LC}$ and $s = \Omega d$ are the resonance frequency and the phase velocity in the line, Ψ_0 is the amplitude of the induced flux, and $\Lambda(x,t)$ is determined by the wave function of the qubit at a given point:

$$\Lambda(x,t) = \langle\psi(x,t)|\hat{\sigma}_z|\psi(x,t)\rangle. \qquad (6)$$

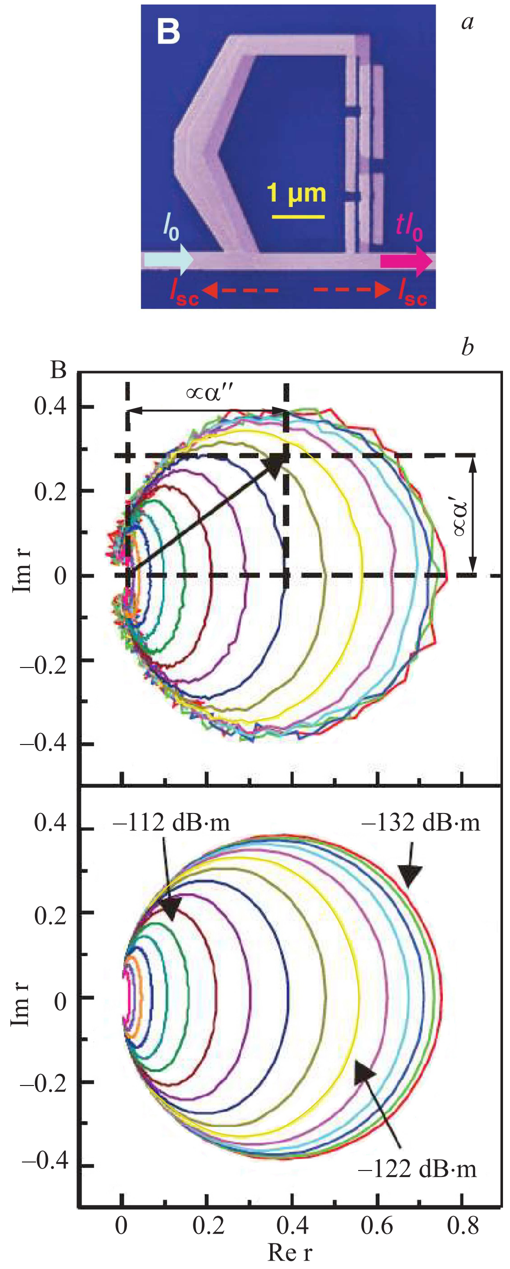

Fig. 2. (*a*) SEM of an artificial atom (flux qubit) coupled to a transmission line. (*b*) Reflection coefficient r as a function of the detuning frequency $\delta\omega/2\pi$ from the resonance at $\omega_0/2\pi =$ $= 10.204$ GHz. The driving power W_0 is varied from –132 dB·m (largest $|r|$) to –84 dB·m (smallest $|r|$) with an increment of 2 dB. (Top panel — experiment, bottom panel — theory). (From Ref. 43. Reprinted with permission from AAAS.)

Analysis of this equation or of its analog obtained for the case of charge qubits [40,41] shows that the qubit line behaves as a special kind of medium — a *quantum metamaterial* — which is sensitive to the quantum state of qubits and capable of producing, e.g., «breathing» photonic gaps due to quantum beats.

Astafiev et al. [43,46] recently confirmed the possibility of the realization of a quantum metamaterial by repro-

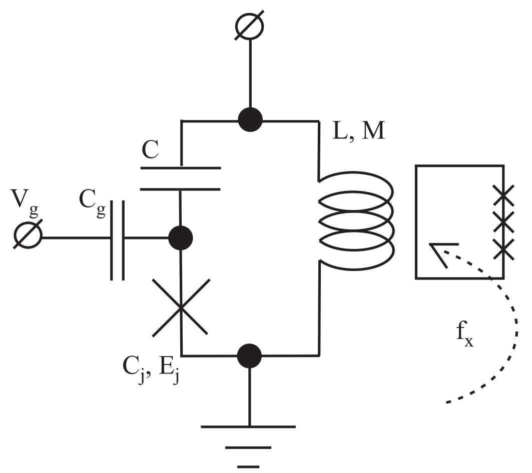

Fig. 3. «Quantistor» is a circuit element with tunable quantum capacitance and inductance (after Ref. 44). Quantum capacitance and inductance of the circuit are tuned by the gate voltage, V_g, which shifts the working point of the superconductor single-electron transistor (charge qubit), and external magnetic flux, f_x, which tunes the flux qubit inductively coupled to the circuit.

ducing in the experiment some effects of light scattering by atoms in the open space, using an «artificial atom» — a flux qubit — inside a transmission line (Fig. 2). Extension of these experiments to the case of a coherent quantum medium consisting of multiple qubits would for the first time allow to realize the dual to the classic diffraction grating experiments, with a *classical* wave now being scattered by a periodic *quantum* medium. Including in the transmission line «quantistors» (Fig. 3) — resonant circuits with both quantum tunable inductance *and* capacitance [44] — adds another interesting feature, a possibility of a quantum superposition of different refractive indices («quantum birefringence»).

In conclusion, the current state of theoretical understanding and of experimental techniques makes possible the fabrication and investigation of macroscopic structures based on quantum coherent solid state qubits as building blocks. The results of such quantum engineering are likely to go far beyond the limited goals presented by quantum computing, and are achievable within the existing state of art. Practical realization of such devices would also provide the most direct way to testing the limits of quantum mechanics.

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