Physical principles of the modeling of three-dimensional microwave and extremely high frequency integrated circuits

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The fundamental principles, physical models, and design fundamentals of three-dimensional microwave integrated circuits are presented. The principles of mathematical modeling of transmission lines and basic elements are discussed. The topological approach to the description of the electromagnetic field in the elements of three-dimensional microwave integrated circuits is examined at the electrodynamic level. The structures of the base elements, functional units, and devices for processing signals from pickups as well as the physical and technological aspects of their fabrication based on three-dimensional microwave integrated circuits are examined.

"There are very few fields left
in science in which we are leaders;
...the number of fields in which
we do not lead is now increasing."
P. L. Kapitsa

I. INTRODUCTION

The evolution of microelectronics can be represented by a rising stepped curve. The curve starts during World War II with the development of metal-ceramic vacuum tubes and the use of printed circuit boards (in the guidance cones of surface-to-air missiles). The first steps on the curve were determined by important discoveries in radio physics and solid-state physics: transistors and strip transmission lines, followed by acoustoelectronic and magnetostatic devices, etc.[1,3] The last steps are associated with the latest achievements in technology, for example, thin- and thick-film hybrid, monolithic (semiconductor) technologies and their modifications,[4–6] as well as new approaches to information processing systems[7–10] up to nonlinear waves and solitons.[11,12] Now these seemingly dissimilar directions are being integrated into a general fast and superfast information processing system (SIPS).[13–16]

Now the cosmic (in the direct sense of this word) hour has arrived for microelectronics, because only if significant progress is made in science and technology in the field of signal transmission over ultralong and ultrashort distances and processing of enormous flows of information in real-time, will it be possible to assimilate and exploit space (and microspace).[4–8,14] It is here that microelectronics is required to achieve the best possible values of the physical parameters: ultrawide band of working frequencies for digital signal processing, high carrier frequency (clock speed), multifunctionality, and minimum mass and size. All these parameters are correlated with one another, but they are controlled by the limiting condition of maximum efficiency with low energy consumption. In addition, there are fundamental limits on the elemental base of modern microelectronics, built on the basis of hybrid and monolithic technologies. These limits are associated not so much with the physical properties of each base element as with the nature of the electromagnetic field generated in larger systems,[15] in particular, with the requirement that the volume for channeling (transmitting) high-frequency electromagnetic field energy must be finite.[16]

There arises the natural question: couldn't Nature be used as an example in the form of the biological structure, for example, of the brain, where signal processing occurs at the level of biological fields? At the present time, of course, the answer is no, since our technology has not yet reached this level of development. But the idea of building three-dimensional structures from basic elements which are coupled by weak electromagnetic fields has itself found a place in high-frequency microelectronics. We shall examine in greater detail the approaches to the solution of this problem from the technical standpoint.

The rate of signal processing is determined by the clock speed, which is being pushed into the microwave and extremely high frequency (EHF) ranges.[17] Specialists estimate that the speed required of SIPS today is of the order of 10^{12}–10^{15} bit/s. Microelectronic devices with these capabilities and in these ranges are technically realizable only with use of integrated-circuit technology (MAs), in which the base elements are continuously interconnected, i.e., they are joined in the plane of the substrate by construction, technologically, and electrically.[13,18] The basic elements of integrated circuits are divided into monolithic and hybrid according to the method of consolidation.

Integrated circuits (ICs) have evolved genealogically from one-dimensional (at the end of the 1940's) to two-dimensional or planar integrated technologies (beginning of the 1980's). It is now obvious that planar ICs have reached fundamental technological limits, mainly with respect to reliability and interconnection problems, as well as mass and size,[19] but most importantly they have reached a fundamental limit with respect to the band of working frequencies,

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which in principle determines the rate of information processing.[1,2] This problem has been solved in the last few decades by means of multiplanar, multilevel, hybrid, and other structures in the form of large-scale integrated circuits (LSIC) and very large-scale integrated circuits (VLSIC).[4,6] The transfer of the ideas and principles of low-frequency microelectronics into the microwave range has not significantly expanded the working-frequency band or improved the mass and size characteristics. This has placed designers at a loss and has forced investigators to search for fundamentally new solutions.

The discovery and detailed mathematical modeling of a large assortment of new types of microwave transmission lines (slot, coplanar, fin-dielectric, dielectric, semiconductor,[13,20-25] and lines with acoustic and magnetostatic waves[24]—and development of monolithic technology on the low-frequency end[19]) have made possible a nontraditional look at the design of microwave electronics devices. The historical development of microwave ICs and the nature of biological information processing systems suggests an optimal variant—utilization of the third dimension in the topology of microwave ICs,[13-17,26] i.e., switching to three-dimensional (3D) microwave and extremely high frequency ICs.[17,27,28]

There now arises the question of whether or not this transition is logical. Electromagnetic fields are intrinsically three-dimensional. Artificial reduction of electromagnetic fields to two-dimensional structures is dictated by the need to simplify mathematical models in order to be able to solve the corresponding boundary-value problems on a computer.[29-36] In planar ICs screens are placed above the two-dimensional (2D) IC in order to prevent radiation leakage to the outside and to avoid parasitic effects due to this radiation. Selective properties are likewise realized by combining 2D ICs with metallic screens, placed in the vertical and (or) horizontal plane. Thus, the third dimension secretly performs its (beneficial) functions even in 2D ICs. This is why the transition to 3D ICs is logical, as is also confirmed, in part, by investigations of biological structures, where the planar distribution of functional units is not understood at all.[37] Therefore, 3D ICs enable signal processing not only in the horizontal plane but also in the vertical plane. As will be shown below, this makes it possible to reduce the mass and size by one to two orders of magnitude and results in a significant increase in the working frequencies and signal-processing speed. Proceeding to the next section, unless stated otherwise, by three-dimensional integrated circuits we mean 3D microwave and extremely high frequency IC's.

2. FUNDAMENTAL PRINCIPLES OF THREE-DIMENSIONAL MICROWAVE AND EXTREMELY HIGH FREQUENCY INTEGRATED CIRCUITS (3D ICs)

2.1. The phenomenon of a three-dimensional integrated circuit

We have already mentioned above the logicality and consistency of switching to SIPS operating at microwave and EHF frequencies, and in the not-too-distant future at optical frequencies also. At the same time 3D microwave (EHF) ICs are an alternative to the strong scientific-technical orientation toward dc or low-frequency LSIC and VLSIC, which, in the overwhelming majority of the cases, have two-dimensional construction.[4,6] Unfortunately, our science and technology is significantly behind in assimilating LSIC and VLSIC at the level of the advanced western countries, and we must generate ideas and develop methods for sharply reducing, if not completely eliminating, this lag. This is also especially important because the possibilities of LSIC and VLSIC (low-frequency and two-dimensional (planar)) which have now been developed and assimilated have been virtually exhausted and these integrated circuits have reached their fundamental limit.[15,19] Superfast information processing systems, which are based on 3D ICs or have a sharply higher clock speed, which ultimately leads to the use of superwideband signals, i.e., essentially to the EHF range and in the future to the optical range, have great functional possibilities. Thus Nature exhibits a dialectical unity of opposite approaches to the problem of constructing superfast information-processing systems.

We note one other, in our opinion instructive, analogy. In reality, the switch to microwave and EHF superfast information processing systems based on 3D ICs is phenomenologically similar to the well-known change of radioelectronic SIPS from analog to digital signals and circuits, with which it is possible to obtain new qualitative results with the "old" elemental base developed for analog systems. Similarly, switching to SIPS based on 3D ICs depends significantly on extensive use of the existing technology of 2D (planar) ICs as well as the device base which has been adopted by industry. Thus switching SIPS to 3D microwave and EHF ICs is both natural and has a good historical basis.

2.2. Definition and general principles of 3D ICs

A 3D microwave and (or) EHF IC is a multiplane (multilevel) module, each level of which is fabricated by the two-dimensional technology, and the base elements within each stage are, as a rule, coupled by galvanic connections while the base elements located in different levels are coupled electromagnetically. The base elements of a 3D IC are made in the form of different types of transmission lines.

This definition largely reflects the level of development of modern IC technology. As this technology is elaborated and improved, 3D microwave ICs will be fabricated in a single technological process, similarly to the manner in which LSIC and VLSIC, operating at relatively low frequency (clock speed), are realized. It should be kept in mind that the development of methods of vertical-injection logic and track methods of implantation of conducting channels into the metal-dielectric filler of a level in a 3D IC will make it much easier to develop the technologies for the general process of fabrication of 3D ICs (see Refs. 4, 39, and 40). The same technologies will make it possible to combine, to a significant extent, the ideas of 3D ICs and microwave-waveguide technology, whose extremely high degree of development of its elemental base will in many ways aid in the development of 3D ICs. On the other hand, the creation of vertical channels will make it possible to realize superwideband elements (interlevel junctions, filters, and resonators, power dividers (summers) or channels, and much more), which the SIPS technology, oriented toward high speed, needs so much. Similar problems also arise in the implementation of SIPS based on monolithic (including both submicron and far (especially from us) nanomicron [sic]) and semiconductor technologies. The problem lies not only and possibly not so much in making channels between the base elements, which is extremely important ("the problem of conductors"), but rather in the development of selective (resonance, strip, etc.) structures, radiating systems, and much else.

We shall now say a few words about the general principles of 3D ICs. The developers of 3D ICs attach special significance to such circuits, because progress is possible only if the general concepts of one or another area of technology and science are understood. For example, 3D ICs are based on two fundamental principles: *the principle of optimality of the base elements and the structural-correspondence principle.*[13] The ideological basis of 3D ICs is the structural-correspondence principle, according to which a 3D IC is a method (approach, method, construction of the microwave and EHF module of a SIPS) for incorporating in the module (logically, structurally, and technologically) the base elements developed specially for 3D ICs together with the base elements traditionally employed in 2D ICs, "standard" microwave technology, devices from quasioptics, optics, and acoustoelectronics, as well as base elements operating on magnetostatic waves, and many other types of elements. Thus a significant distinction and advantage of 3D ICs over other designs of microwave modules in SIPS is that virtually the entire enormous arsenal of both existing base elements and functional units as well as everything that will be created in the process of development of microelectronics and allied fields of science and technology can be used in 3D ICs. We emphasize that this pertains equally to both engineering and technology. Possibly, this concerns more the technology, in which we lag most seriously behind our foreign competitors, who, it looks like, are not planning to "share" with us these achievements under any circumstances. This is why it is important to have a philosophy and a technology that could assimilate any technologies and would make it possible to realize on their basis SIPS which are close in quality to their fundamental limits.[39,40]

We note that the structural-correspondence principle is close in meaning and, possibly, significance to N. Bohr's correspondence principle, which is well known in physics and according to which any new physical theory must incorporate preceding theories and results as special cases.

The other fundamental principle of 3D ICs is the *principle of optimality of the base elements*. The point is that by the time 3D ICs appeared a large number of different types of transmission lines had already been proposed, developed, and applied in microwave and EHF technologies, quasioptics, and optics. It became obvious that a new general approach to the construction of microwave modules, so as to make the most of the advantages of base elements based on different types of transmission lines, is required. The requirement "to each base element—a transmission line optimal for it" was born, and this requirement ultimately formed the essence of the principle of optimality of base elements. It is true, however, that the question of the realization of junctions, fabricated on the basis of different types of transmission lines, between neighboring base elements remains open. It is well known that such junctions are some of the most complicated and cumbersome devices in microwave technology. It is natural that the development of SIPS in the 2D variant is a utopia, and we do not say this as a joke. Indeed, utopias of 2D ICs whose base elements are constructed from different types of transmission lines can be easily discerned in at least two circumstances. First, it is impossible to form an enormous number of junctions between slot strip lines while remaining within the concept of a 2D IC. This fact is obvious and is confirmed by the entire history of the development of the traditional waveguide technology. Hence there follows immediately a second decisive circumstance—a 2D IC requires switching to a three-dimensional construction and the entire question is whether or not such a transition can be made natural. The idea of a 3D IC is precisely such a constructive proposition.

We wish to make one final remark. In concluding this section we underscore once again that the idea of a 3D IC is suitable for any (existing and, especially, future) technology. Of course, a hybrid integrated technology for 3D ICs is not natural because of the suspended mounting of active, nonlinear, and other devices, and in this variant suspended boards must be provided or higher "ceilings" must be set aside for them in special levels of the 3D IC, etc. Universal adoption and use of, for example, monolithic semiconductor ICs will open up for SIPS based on 3D ICs enormous prospects for improving the mass and size characteristics, increasing the speed and reliability, etc. This can be seen especially clearly for the examples of LSIC and VLSIC mentioned above.[41] Finally, it is difficult not to agree with the view that the degree of integration of microwave microelectronic devices can be further increased by switching from 2D to 3D microwave ICs in which the base elements are placed between the layers of dielectric and magnetodielectric substrates. In particular, beam-forming matrices of microwave antennas as well as analog and digital SIPS can be developed on the basis of 3D ICs.[38]

2.3. Transmission lines for 3D microwave and EHF ICs

The general considerations stated above regarding 3D ICs indicate that such circuits contain a large number of different types of transmission lines. There are of the order of 100 canonical types of lines, and if their modifications are taken into account, then the number is at least an order of magnitude higher.[13,36] Moreover, the advent of 3D ICs is largely attributable to the existence of many different types of transmission lines, because it was necessary to have a "convenient" general idea of the construction of a microwave module capable of incorporating base elements based on different types of transmission lines without the use of special transitional devices.[1]

Here we shall consider, naturally, only a limited number of different types of transmission lines. Some examples of transmission lines employed in 3D ICs are shown in Fig. 1. Structures with anisotropic filling of a level of the 3D IC or the cross sections of the transmission line,[31] dielectric and periodic transmission lines,[30,36,42] and many others are also employed in 3D ICs. We shall examine, first, the transmission lines most often employed in 3D ICs and, second, new and promising transmission lines.[1] One can see, for example, from microwave waveguide technology how complicated the junctions (necessarily three dimensional) between different types of waveguides are.[42-45]

One of the main parameters of a regular transmission line (and the base element based on it) is the loss per unit length. This quantity consists (in the overwhelming majority of the cases additively) of losses due to heating (of the

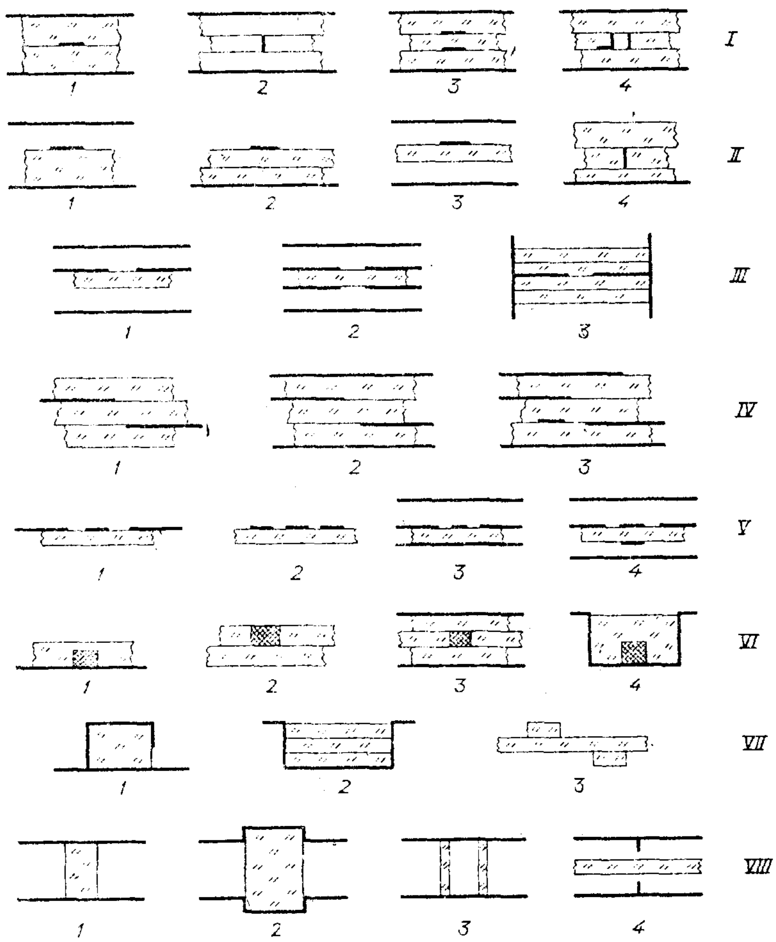

FIG. 1. Principal classes of transmission lines employed in 3D microwave and EHF ICs.

metal and dielectric) and radiation losses. In the base elements connecting regular and irregular sections of base transmission lines there occur additional losses due to conversion into leaky waves, losses due to unsanctioned couplings between base elements (the same or different levels of the 3D IC) on the fundamental or parasitic waves, etc. Comparative assessments of losses in different types of transmission lines are presented in Ref. 48.

The data on losses in different transmission lines give rich food for thought. They depend significantly on the configuration of the electric field in the transverse section of a transmission line. Unfortunately, the losses in one of the basic and natural (for 3D microwave ICs) lines—*unsymmetric slot line* (USL)—have not been thoroughly studied. Although USLs have been studied quite well both theoretically and experimentally (see, for example, Refs. 13, 46, 47, 69, 70), the problem of taking into account adequately losses in USLs nonetheless remains. Approximate calculations show that the losses in a USL are slightly higher than losses in a symmetric slot line (SSL). This pertains equally, and possibly even more so, to systems of coupled USLs, upon which the basic classes of base elements of 3D microwave ICs are built.[13,42,43,45–47]

For quite a long time it was thought that an insulated rectangular dielectric waveguide (DW) was the most convenient type of transmission line for the microwave range. However, even in the development of the simplest devices, for example, a directional coupler based on two coupled DWs, it was found that such a structure is very sensitive to, for example, mechanical loads, it requires systems for securing both DWs in position, and so on. This engendered the idea of a mirror DW, which has a metal or more complicated (for example, multilayer) base; later, bilateral structures came into use: "mirror" DWs based on different metallic or dielectric substrates.[13-23,42-54]

Three-dimensional microwave ICs are implemented primarily on the basis of one or two basic models—screened and unscreened (Fig. 2). Of course, a combined variant of a 3D IC, in which a metallic screen is present between some

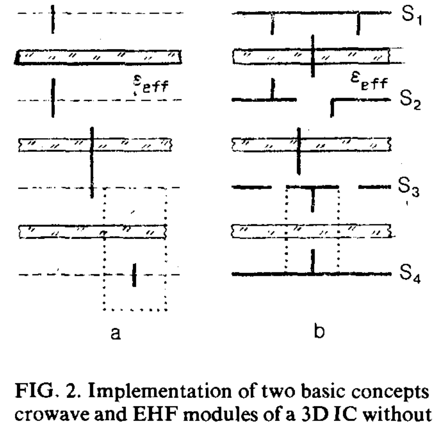

FIG. 2. Implementation of two basic concepts of the construction of microwave and EHF modules of a 3D IC without interlevel screens (a) and with interlevel screens (b).

stages of the circuit (Fig. 2b) and no screen is present between other stages of the circuit (Fig. 2a), is also possible. In the unscreened version of a 3D IC module, windows or systems of windows (openings) are set up in order to organize electromagnetic and, possibly, galvanic coupling (for example, with the use of a ridged dielectric line[21,23,36,42,55,56]) between base elements located on different levels at definite locations of the interlevel screens. The required degree of interconnection between the base elements is achieved with the help of these openings. In the process, such an interlevel junction usually performs some additional functions, for example, it acts as a band-pass and (or) polarization filter, coupler, and so on. In the unscreened scheme of an EHF 3D IC, layers of magnetodielectric, which maintain the surface wave, ensure that the field extends over a quite short distance in the vertical direction, and consequently there are no unsanctioned interlevel couplings. The screened version of 3D ICs can be referred, very arbitrarily, to the centimeter and millimeter ranges while the unscreened version can be referred to the submillimeter range. The wave-maintaining layers can alternate with layers having significantly lower permitivities. Such a construction imparts an additional stiffness to the structure of the 3D IC (of course, at the expense of some increase in the dielectric losses).

Three-dimensional microwave ICs can be constructed on the basis of a mirror dielectric waveguide (with finite transverse dimensions), but on general circuit-design principles circuits that can be formed on some single (metallic, dielectric, or "impedance") base have been found to be preferable (Fig. 3a). Another point is that different "superstructures" of the type finite magnetodielectric or impedance overlayers, metallic continuous or "reticular" guiding formations, etc., can be included in such a construction (in the spirit of the structural-correspondence principle). It should be noted, in general, that periodic (impedance) and anisotropic structures become more important in 3D EHF ICs.[13,31,34,36,48,53,54] They are used as waveguiding structures, emitting elements (with the required three-dimensional feeding scheme), interlevel junctions functioning as band pass and (or) polarization filters, and so on. Examples of periodic microwave and EHF structures are presented in Ref. 53. The simplest structure is a periodic grating of finite width on a magnetodielectric layer, on whose reverse side a metallic or impedance screen can be placed directly or at some distance from it. The grating can be a double grating, i.e., it can be placed on both sides of the layer. Combined structures, in which are employed periodic structures of the type generalized coplanar line, are also possible.

The foregoing review is by no means complete. An entire book is required to give a brief exposition of the existing results on transmission lines for 3D microwave and EHF ICs, and we refer the reader to the references.

3. PHYSICAL MODEL OF 3D IC STRUCTURES AND DESIGN PRINCIPLES

A radioelectronic system contains, as a rule, power sources (including secondary sources), low-frequency (digital) and high-frequency digital and analog parts, as well as external actuating devices, including emitters, which are made in the form of separate functional modules.[36,38,42,53] In a three-dimensional structure these modules become structurally consolidated, and in addition we must not lose their prescribed functional properties or the couplings between them. Thus this consolidation must be performed according to definite rules of modeling and principles of design of multifunctional 3D ICs.[13,40] But before we examine these laws and principles we must examine the physical model of 3D SHF ICs.

In the present review we focus our attention primarily on analysis of the topological approach to 3D ICs. This approach is relatively new, and it is not employed every day in general electrodynamics, especially in the design of ICs and 3D ICs. At the same time, it makes it possible to find not only the structure of the field, but it also often shows the construction of the base elements. Of course, in order to determine the scattering matrix and the composition of the base elements it will be necessary to employ also the "traditional" electrodynamics of microwave—EHF structures (see, for example, Refs. 13, 35, 42–45). These approaches are reviewed in the lectures in Ref. 54. We note only that, first, the "standard" procedure is put at the top of the list: the system of integral equations—Bubnov–Galerkin method—and a system of linear algebraic equations with its subsequent reduction. Second, there are all the techniques that have al-

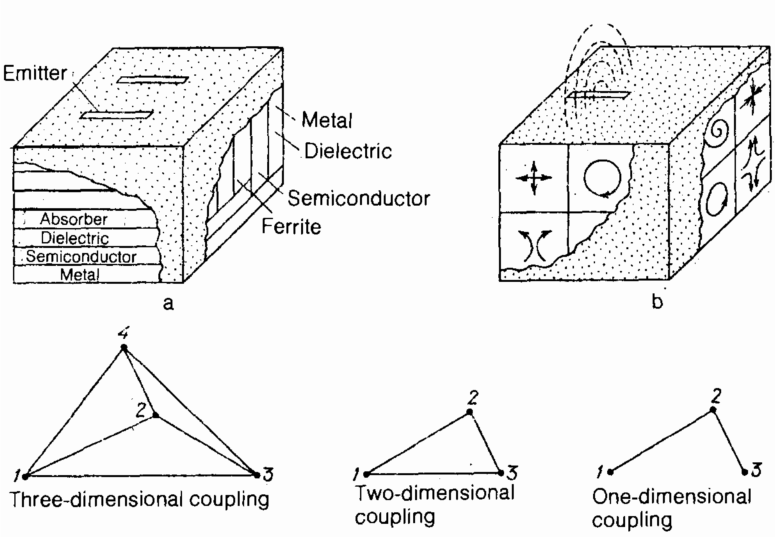

FIG. 3. 3D microwave IC: a) arrangement of layers; b) key field structures; and c) types of couplings between base elements.

ready been developed, ranging from heuristic approaches to exact numerical, numerical-analytic, and analytic methods. The number of such methods is enormous, but nonetheless the basic methods are probably contained in Refs. 13, 25, 29–36, and 42–57 and in the references cited there.

We wish only to underscore one thought which may seem trivial, but we know from many years of experience that no method and approach mentioned above will work until the physics of the operation of transmission lines, base elements, and so on is understood. Once the physics is understood, we can proceed to the design stage. Here the topological approach could be very helpful.

Waveguiding transmission lines, whose current-carrying conductors lie between layers of active and passive inclusions of the 3D microwave IC, make up the other part. Depending on the physical properties of the base elements and the topology of the conductors of a 3D IC, a complicated electromagnetic field structure, which reduces to a collection of separatrices of the lines of force, nodes, centers, and saddles, is formed (see Fig. 3b). The simplest combinations of these structures are characteristic of the fields of waveguide, coaxial, dielectric, symmetric and unsymmetric strip (SSL and USL), as well as symmetric and unsymmetric slot (SSlL and USlL) transmission lines. The latter lines have proven themselves especially well in 2D microwave ICs.[29,45,53,54] In 3D ICs, however, their functional possibilities are inadequate, and this has stimulated the investigation and application of finned-slot transmission lines and representatives of a new class of base elements with a three-dimensional topology.[20–23,26,40,46,58] All transmission lines enumerated above, including transmission lines based on surface acoustic and magnetostatic waves, match well with them.

Finally, the last key item in the definition of a 3D IC is the three-dimensional coupling of base elements via the field. This 3D coupling must play, aside from its basic role, an additional functional role. For example, couplings with a decrease in the amplitude of the field (an attenuator), with a phase shift (a phase shifter), with a change in phase and amplitude simultaneously (a directional coupler, filter, etc.) are realized.

Thus it is possible to single out a static form of coupling, such that when electromagnetic energy is transferred along the coordinate r into the vertical plane, the parameters of the signal—the phase v, the frequency f, and the amplitude H_0—remain constant ($dv/dr = df/dr = dH_0/dr = 0$) and the functional form of the coupling, where any signal parameter or a combination of the signal parameters change from point to point in space, has the form $dF(v,f,H_0)/dr \neq 0$.

The directional distribution of couplings can be represented in the form of an oriented graph between base elements (Fig. 3c). The simplest graph is a tetrahedron—a simplex of a complicated three-dimensional interconnection. The base elements occupy the vertices, and the edges are the coupling vectors. A tetrahedron of interconnections can also be formed in 2D circuits, but then there arise problems in realizing intersections of the conductors. For this reason, the simplex of 2D circuits is a triangle or segment (see Fig. 3c) while in the case of 3D ICs the natural simplex is a tetrahedron.

The introduction of three-dimensional functional couplings between the base elements results in unification of the functional units of a 3D IC and significantly extends the limits of application of the radioelectronic systems approach. Thus a new concept arises—architectonics of 3D ICs, the science of the interaction of electromagnetic interconnections and their quantitative relations between the base elements of a three-dimensional structural system.[16] On the basis of their electromagnetic nature, the fundamental and higher-order waves, surface and volume waves, as well as acoustic and magnetostatic waves, i.e., even waves which are not sanctioned (i.e., they are parasitic) in 2D microwave ICs, can play a sanctioned coupling role in 3D ICs.

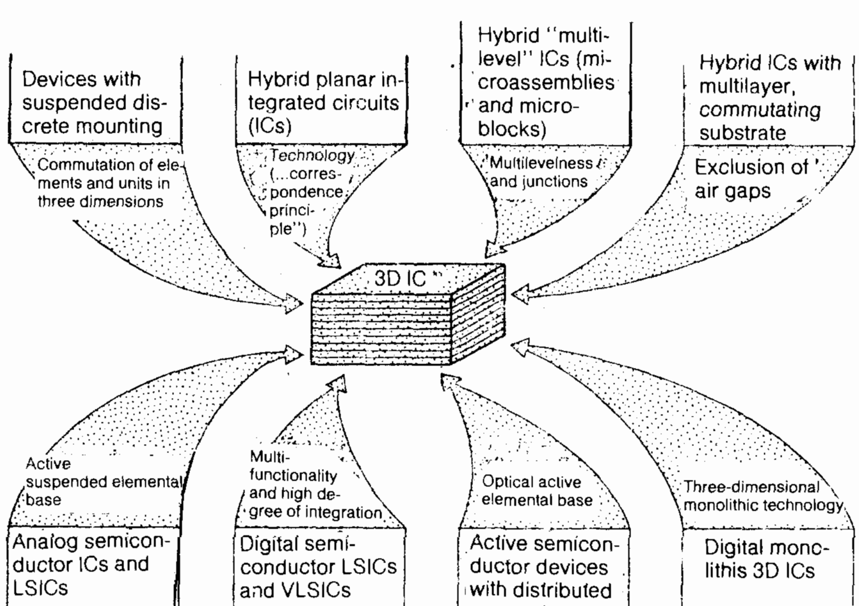

FIG. 4. Diagram of incorporation of commercially developed solutions to technological and structural problems into 3D microwave ICs.

The foregoing analysis of the definition of a 3D IC allows us to proceed to the study of design questions, which initially presuppose that to prescribed characteristics there is associated a definite structure of couplings between base elements. The choice of questions presupposes in-depth knowledge and the ability to solve extremely complex three-dimensional problems in analysis and synthesis. The multi-facetted nature of the latter problem makes it necessary to use not only superfast computers, but also to develop fundamental principles for the design of 3D ICs, taking into account technological factors.

We now make a few additional remarks about the basic principles of 3D ICs: the structural-correspondence principle and the principle of optimality of base elements. The highly developed structure of a 3D IC from the viewpoint of the structural-correspondence principle is illustrated in Fig. 4, where the basic achievements of existing designs in 3D ICs are singled out: technology, elemental base, interconnections between base elements, etc.

Optimality of the construction of 3D ICs presupposes the use of a combination of different types of transmission lines in a single base element or in a bundle of base elements. In addition, the structures of the fields in transmission lines differ significantly. Active elements which differ not only structurally,[59,60] but also according to the polarizations of the fields at the inputs and outputs, participate in the structure simultaneously. There arises the typical situation in which it is necessary to combine two or several transmission lines in which the fields of the working waves have different topologies, requiring the corresponding matching base elements, which, as a rule, narrow the frequency band and increase mass and size. This can be avoided, if the transmission lines and (or) base elements are arranged in the space of the 3D IC in a manner so that the patterns of the electric and magnetic fields coincide in the coupling plane. For example, an orthogonal arrangement of a slot line and a transmission line in the layers of the dielectric with magnetic-field coupling or a coaxial arrangement of a slot line and a coplanar line (CL) with electric-field coupling will be optimal.

The situation is somewhat more complicated in the case of active elements, because their choice is limited and the matching must be very precise. The introduction of matching base elements leads to the above-noted drawbacks and often appreciably decreases the functional possibilities of active elements. The way out of this situation is to select an optimal type of transmission line for active elements whose electric fields are polarized in the junction plane. Here the base elements can be both active and passive elements: diodes and transistors, resistances, and capacitances, inductances and segments of transmission lines, and so on. For example, serial connection of a diode requires a strip line, parallel connection requires a slot line, a transistor requires a coplanar line, and so on.

Of course, on in the transition from 3D to 2D ICs the principle of optimality of the base elements becomes less effective as a means of formalizing the design, since 2D ICs are realized, as a rule, on a single (base) type of transmission line.

The three-dimensionality of the structure of a module based on a 3D IC and its separate functional units encourages designers to use as extensively as possible the criteria of usefulness and elegance, thereby bringing the layout procedure closer to the process of constructing a reasonable architectural ensemble of base elements.[13,30,31,34,60] In this respect, it is customarily considered that the design of 3D ICs is much more an art than is the design of 2D ICs.[13,40]

4. MATHEMATICAL MODELING OF 3D SHF ICs

Having developed several general principles of approaching the problems of modeling 3D ICs, on which we focused the reader's attention in the preceding section, we still wish to mention some details of this process. First, the aim of the modeling of 3D ICs is to investigate the electrodynamic characteristics on the basis of a prescribed internal structure of the physical model. The main parameter is ordinarily considered to be the complete scattering matrix S, which represents the ratio of the incident signal power to the transmitted or reflected signal power. The scattering matrix contains complete information about the physics of the operation of a base element or the device as a whole. Because of the greater complexity of the internal structure of 3D ICs and the average character of the information contained in the S-matrix, recently the geometric characteristics of the electromagnetic field, which are distinguished by their unique physicomathematical "intuitiveness" (Refs. 20, 25, 71, 72), have come to the fore.

The development of a definite mathematical formalism for describing the structure of the electromagnetic field equips the investigator with a powerful apparatus for clarifying the physics of the operation of the base elements of 3D ICs.

Many problems which are characteristic of 2D microwave electronics are also inherent in the modeling of 3D ICs, but in the latter case they are exacerbated by the higher dimension of the problem. The difficulties in solving these problems are formally connected with the three dimensionality of the domain of the systems of partial differential equations, and not only do they require the use of fast modern computers, but in addition the investigator and designer must have good "physical" tools and intuition.

Two approaches to solving these problems can be tentatively singled out. In the first approach the problem is formulated exactly, for example, with the help of Maxwell's equations or their integral analogs, or finally by writing Maxwell's equations in a nontraditional (for electrodynamics) form using differential forms (exterior algebra[61]). Next, in the solution process the exact operator can be replaced with an approximate, but asymptotically close, operator. Typical examples are Galerkin's method for integral equations, the method of singular integral equations, the method of finite elements and differences, the method of small autonomous blocks, and so on.[29-35,61-67]

The application of approximate methods for solving the problems of the electrodynamics of 3D ICs, in spite of the formally exact initial apparatus, requires the use of an entire system of physical criteria for weeding out possible spurious solutions engendered by the approximation of the operator or for solving the problem. Various algorithms exist for this purpose: form introduction of special terms, compensating, for example, the discrete nature of the approximation into the algorithm up to controlling the patterns of the lines of force of the solutions obtained for the characteristic waves.

In order to develop a specific representation of a mathematical model of a 3D IC we present one of the algorithms of this type.[13,46,47,68–70]

A complicated multilevel transmission line for a 3D IC can be divided into a series of elementary layers, whose boundaries naturally coincide with the interfaces of dielectrics and metallic conductors (see Fig. 3a). In each region Fourier series are written down for the longitudinal components of the electric field E_z and magnetic field H_z:

$$E_z^{(i)} = \sum_{n=1}^{\infty} A_n^{(i)} v_n^{(i)}(x, y) e^{-jk_z z} \quad , \tag{1}$$

$$H_z^{(i)} = \sum_{n=0}^{\infty} B_n^{(i)} u_n^{(i)}(x, y) e^{-jk_z z} \quad . \tag{2}$$

In Eqs. (1) and (2) A_n and B_n are unknown coefficients, k_z is the longitudinal wave number, v_n and u_n are orthonormalized functions which satisfy the boundary conditions everywhere except on the surfaces of the separated ith layers, on which the surface electric fields $e_t^{(i,i+1)}$ and $e_t^{(i,i-1)}$ are specified. Next, using the orthogonality of the functions $v_n^{(i)}$ and $u_n^{(i)}$, the coefficients $A_n^{(i)}$ and $B_n^{(i)}$ are expressed in terms of the Fourier coefficients of the tangential fields $e_t^{(i,i+1)}$ and $e_t^{(i,i-1)}$. The newly obtained formulas for fields of the type (1) and (2) are consistent in the sense that the tangential electric fields are continuous, but their magnetic fields are discontinuous even in the absence of electric conductors. Requiring, formally, that there be no such discontinuity of the tangential magnetic fields on the slots, we obtain a Fredholm integral equation of the first kind:

$$\sum_{n=0}^{\infty} \int_S e_t(x') \hat{g}(x, x') \mathrm{d}x' = i(x). \tag{3}$$

In Eq. (3) $\hat{g}(x,x')$ is the Green tensor and $i(x)$ is the electric current, which vanishes outside the conductors. We note that Eq. (3) is an exact model of the guiding structure of the 3D IC, if $e_t(x')$ belongs to the set of fields of the characteristic waves. In practice, however, an approximate distribution of the fields is constructed in the form of a finite sum of basis functions with unknown coefficients:

$$e_t = \sum_{i=1}^{2} \sum_{m=1}^{M} a_{mi} e_{mi} x_i, \tag{4}$$

where i and m enumerate the unit vectors in the Euclidean and functional spaces, respectively.

Applying Galerkin's method to Eq. (3), we substitute the expression (4) and minimize the residual between the integral equation and the orthogonalization of its system of basis functions from Eq. (4). The obtained system of linear algebraic equations is meaningful only if its determinant vanishes. The latter relation is the dispersion equation for the desired longitudinal wave number k_z. It should be noted that in spite of the seeming vigor of the algorithm, there are many methods for realizing the algorithm, especially, with respect to the choice of types of basis functions. Without giving a fantastically extensive bibliography on this subject, we can recommend piecewise-definite basis functions, at least on the basis of the fact that such functions are more flexible in practice, and the convergence is good for a number of configurations of guiding structures. Examples of the application of such functions are contained in Refs. 13, 46, 47, and 68–70; an electrodynamic theory of characteristic waves of a screened USIL and its modifications is also given there.

The study of the system of characteristic waves is a necessary but by no means sufficient problem of modeling of 3D ICs. The next step is to develop models of nonuniformities in transmission lines.[29,30,35] One method for calculating the S-matrix of these base elements of 3D ICs is to expand the field to the left and right of the nonuniformity, such as a jump in the geometry of the conductors, in series of characteristic waves, equating the tangential fields in the plane of the jump, and to minimize the residual of this difference by Galerkin's method.[35,36,38,47] Two drawbacks of this method are that the algorithm converges slowly and it often gives spurious solutions. In the last few years a number of nonuniformities of the type associated with the open end of a microstrip line have been modeled with the help of two-dimensional integral equations, which make it possible to take into account the singularities of the currents on the edges of conductors having a complicated configuration.[72,73] We note that combining exact electrodynamic methods with conformal transformations is especially effective for taking into account a complicated configuration.[36,40,42–44]

Electrodynamic models and the information obtained with their help undoubtedly determine much of the construction of 3D ICs, but designers are wary of the complexity of the calculations and the lack of intuitiveness. This is why, in spite of the obvious success of the computational technique and methods, approaches, conventionally termed similarity or analogy methods, are at the present time more popular in microwave radio physics. The first attempts in this direction go back to the 19th century; they are associated with the names of the founders of the theory of electromagnetism M. Faraday and J. C. Maxwell. Maxwell gave the clearest definition of the method of analogies: "Similarity, which is the basis of an analogy, exists not between the phenomena themselves, but between the mathematical relations describing these phenomena" (Ref. 44, p. 263). We note that analogies between the patterns of the lines of force and the streamlines of a moving liquid played an important role in Maxwell's deliberations.

Thus the fruitfulness of the similarity method was "elucidated" by the classical investigators of electromagnetism. The essence of this method can be briefly expressed as replacing the operator Φ with an operator F close to it which gives a solution x_F in a definite range of parameters, so that $x_F \sim x_\Phi$. The operators Φ and F are close in the sense $|x_F - x_\Phi| \ll 1$. In practice an entire series of similarities is sometimes employed to construct a model of the object. Quasistatic models of 3D ICs are a typical example. In such models, first, the hybrid character of the field (e,h) of a real waveguiding structure is neglected and a planar field $(E^{\sim}, H^{\sim})$ is associated with the structure. Second, the harmonically varying field is identified with a constant field (E^{-}, H^{-}), whose currents, however, flow only on the surfaces of the conductors. Finally, an analogy is drawn between the static currents and charges on the conductors $(i \to q)$. This makes it possible to investigate many base elements by the methods of conformal transformations and network theory.[23–26,29,30,33,36,40,44]

Thus the diagram of similarities between boundary-value problems for the Helmholtz and Laplace (Poisson) equations is as follows:

$$(\mathrm{e}^{\sim}, \mathrm{h}^{\sim}) \to (\mathrm{E}^{\sim}, \mathrm{H}^{\sim}) \underset{i \to q}{\to} (\mathrm{E}^{-}, \mathrm{H}^{-}),$$
$$\nabla^2 + k^2 \to \nabla^2. \tag{5}$$

There arises the question of the correspondence between such models and their objects—three-dimensional integrated circuits. This question can be answered only by comparing with exact theoretical or reliable experimental results.

A widely used version of the similarity method is Oliner's method, developed at the beginning of the 1950's for calculating the parameters of base elements based on strip transmission lines. The crux of the method consists of replacing an open transmission line with an equivalent rectangular waveguide, whose theory was developed in analytical form. Here some boundary conditions are replaced with other boundary conditions while the operator of Maxwell's equations is prescribed "accurately." In order that Oliner's model correspond to the physical model it is required to satisfy a number of conditions based on physical considerations: the characteristic impedance of the object is equal to that of the model, the transferred power is concentrated in a cross section bounded by "magnetic" walls, and the volume is filled with an effective medium so that $e_r \to e_{\mathrm{eff}}$. The algorithm developed on the basis of this method is called the generalized Oliner method.[29,30] An important feature is that because the key problem of the incidence of a wave on the edge of a semiinfinite structure is solved exactly the required positioning of the "magnetic" wall is known exactly.[30] Thus the assumption that the transmission line under study operates in the single-wave regime makes it possible to reduce the three-dimensional analysis to a two-dimensional analysis. We shall examine in greater detail the "effect" of Oliner's method.[30] The physical basis of Liner's heuristic approach is the assumption that the energy of the working wave of the strip line is concentrated near the strip conductor or near the nonuniformity of the transmission line. An equivalent waveguide or coaxial structure is formed for each specific transmission line. The solution of the electrodynamic model problem is sought for the equivalent structure—Oliner's model. Specific characteristics of the physical-topological model[44] of each specific transmission line studied are taken into account in Oliner's model. In addition, the model is a better one to the extent that the transmission line is "closed"; this follows from the heuristic character of the method: In a real physical-topological model of an open transmission line the local energy characteristics of the principal working type of wave are more important the topological parameters in the cross section of the transmission line. Thus in the method "quasistatic mapping of the object onto the model—solution of electromagnetic model problem" which is basically a combined method, the first method preserves the "total" information about the energetic basis of the transmission line studied and fairly complete information about its topological parameters. In the second electrodynamic method one constructs the characteristic types of waves, which differ from the waves actually observed in the transmission line under study but converge to them in the energy basis. This explains the effect of applying the exact electrodynamic method, for example, in the problem of synthesis of 3D ICs and their base elements—the optimization of the parameters of the rigorous electrodynamic method to structures approximated with a one-wave operating regime by means of the carrier of the physical-topological information–to the generalized Oliner model, which is constructed in the quasistatic approximation using conformal transformations. This interpretation makes it possible to delineate more clearly the range of application of both Oliner's method itself and its generalized variant.[30]

The question examined above has made it possible to develop an electrodynamic theory of SSL and USL as well as the base elements based on such lines.[13,30,36]

The next step in the development of the similarity method was to introduce a third condition: the cut-off frequency of the equivalent waveguide must be equal to the cut-off frequency of the transmission line under study.[13] This made it possible to develop an entire class of nonuniformities on transmission lines with longitudinal components of the electric or magnetic fields.[14]

The experience gained in modeling 3D ICs by similarity methods makes it possible to formulate a number of general principles for constructing such models in application to diverse base elements. One such principle is homeomorphism of the structure of the electromagnetic field of the object (T_0) and its Oliner model T_{m}, so that $T_0 \leftrightarrow 3T_{\mathrm{m}}$. In what follows by structure of the electromagnetic field we mean its topological scheme; this is closely associated with basic symmetry principles: Noethers theorem and Birkhoff's theorem, the law of compensation of symmetry, the principle of dissymmetrization, and so on. For the subsequent arguments the Neumann–Minnigerode–Curie (NMC) principle is important. This principle reads as follows: "A necessary condition of symmetry of a physical phenomenon with respect to a group of transformations (f_{T}) is that, in the present case, the structure of the field must also be symmetric under the same transformations."[76] We now prove the essential validity of the principle of invariance of the topology of the field in the similarity method.

Theorem. A necessary condition for the realization of similarity between the physical properties of a base element and its model is that the structures of their fields must be homeomorphic:

$T_0 \leftrightarrow T_{\mathrm{m}}$.

Proof. Let the object have P_0 significant physical principles and a model P_{m}. We now determine whether or not the homeomorphism $f_{\mathrm{T}}: T_0 \leftrightarrow T_{\mathrm{m}}$ is a necessary condition for the physical properties P to be invariant:

$P_0 \leftrightarrow P_{\mathrm{m}}\ (f_{\mathrm{T}}: T_0 \leftrightarrow T_{\mathrm{m}})$.

The problem reduces to determining the symmetry of the physical properties P relative to the homeomorphism f_{T}. For the proof we use the NMC principle, in accordance with which we have necessity of invariance at least for some of the physical properties in the case of the homeomorphism f_{T}: $T_0 \leftrightarrow T_{\mathrm{m}}$. The theorem is proved.

Combining the results of the theorem with the preceding arguments, we note that in both cases an essential element is the approximateness of the correspondence of the object and the model (Oliner's). This does not contradict the NMC principle itself: owing to their abstract nature the conditions of symmetry are only necessary but they are insufficient for realization of the phenomena.[76] Thus, formal analysis of the symmetry conditions does not remove the necessity of carefully studying the physical phenomena themselves.

The validity of this theorem is illustrated by the examples presented above. For instance, a strip line is associated with a rectangular waveguide with magnetic walls, whose principal wave is a T-wave, for which there is a cut-off frequency. The Oliner's method for a SSlL requires not only that the type of wave in the model be matched with the model, so that the structures of the fields would be compatible in the working frequency range. Sufficiency in the similarity between the objects and models is achieved by matching other parameters also, for example, by placing the magnetic walls of the model of the strip line at some effective distance corresponding to the storage of the reactive power.[30] We note that the accuracy of the approximate models is satisfactory for a large number of practical examples only for frequencies up to 10 GHz. However, the remark made above about the rigorous solution for the key structure largely removes this restriction.

Having examined the basic approaches to modeling 3D ICs, we now examine their role in the current and future design of microwave radioelectronic apparatus. It is well known that design is predicated on the development of an internal structure of the object according to its prescribed wave characteristics, for example, the amplitude versus frequency characteristics. On this level, the method of similarity between microwave structures and equivalent low-frequency networks has an indisputable advantage, since to the prescribed frequency characteristic there is associated a low-frequency circuit, and the microwave device is reconstructed according to it. In addition, the stage of qualitative (prototype) synthesis does not require significant computer time, and the mathematical and physical apparatus employed at this stage is more easily understood by the design engineer than the electrodynamics of 3D ICs. Nonetheless, the use of low-frequency analogies at this stage of synthesis of the object being designed immediately restricts the class of possible solutions: the richness of electrodynamic effects which are capable of giving a new, better solution is lost. The fundamental limitation of similarity methods lies in the fact the solutions are limited to a definite class. In order to go beyond this class the designer must, at least, think at the electrodynamic level and he must have a clear and precise understanding of the physics of 3D ICs.

Does the classical electrodynamic approach provide the means for this? In answering this question we can only say that the potential is there. The point is that for a long time it was considered that the scattering matrix S was the only output characteristic of the model. As electrodynamic models came into use, it became necessary to analyze multimode matrices, so that the number of characteristics increased several-fold. In switching to electrodynamic models the designer often loses a unique and physically clear representation—the model of the device, and for this reason it is necessary to return repeatedly to qualitative synthesis based on equivalent circuits. The circle closes and with the exception, perhaps, of higher accuracy of the solution, obtained at the cost of astronomical amounts of computer time, with no clear global advantages obtained.

Thus 3D microwave ICs and their physics require new approaches, capable of providing precise and clear physical models and a new electrodynamic design strategy. One such approach is intensive use of topological schemes of the electromagnetic fields in the theory and practice of 3D ICs.

5. TOPOLOGICAL APPROACH IN THE DESIGN OF 3D MICROWAVE ICs

Three-dimensional ICs are very complicated objects from the viewpoint of mathematical modeling and synthesis of diverse structures. This makes it necessary to forsake exact mathematical models without, in so doing, violating the physics. These approaches have their own areas of application, but none of them depend on the electrodynamic apparatus. For example, quasistatic models neglect the real dispersion of the phase velocities. Oliner's models are largely inaccurate at high frequencies, especially for comparatively complicated transmission lines, and the use of exact solutions requires that the designer think at the "electrodynamic" level. It is thus very important to develop theories and models of 3D ICs which depend on the exact electrodynamic apparatus, but which give a clear picture of the physics of the processes. The history of modern physical science clearly shows that such a rigorous theory of internally complicated objects, such as 3D ICs, must still be abstracted from a number of details. However, the degree of abstraction should not affect and cut off significant features of the physics of 3D ICs, as happens in quasistatic or simple Oliner models. As an example of such an approach we propose a theory that is based on the apparatus of topology, in which the objects are the configurations of the electromagnetic field.[20,71,75,77-79]

By definition, the topological network is a collection of separatrices and positions of equilibrium of the phase volume of the equation of the lines of force

$$\frac{dr_e}{dt} = e, \quad \frac{dr_h}{dt} = h, \tag{6}$$

where e and h are the electric and magnetic fields, respectively, and r_e and r_h are the vectors of their lines of force.

Since the formula (6) describes autonomous dynamical systems, the qualitative theory of ordinary differential equations,[80] which have their own specific character governed by the electrodynamic nature of the transmission lines, is fully applicable to them. This requires the development of a special mathematical apparatus based on the topological form of Maxwell's equations. The local topologies of the fields near the general points of equilibrium have the form $e = h = 0$. They are obtained by expanding the fields e and h in a Taylor series and substituting into an equation of the type $f(l_e, l_h) = 0$, where l_e and l_h are characteristic numbers of the positions of equilibrium of the electric and magnetic fields, respectively. It is important to note here that the choice of the general point of equilibrium $e(r_0) = h(r_0) = 0$ ensures that the relations obtained are invariant under the general Lorentz group. Maxwell's equations in topological form are as follows:

$$\det[\hat{A}(l_e, h) - l_{h,e}\hat{E}] = 0; \tag{7}$$

here $\hat{A}$ and $\hat{E}$ are general and unit matrices, respectively. Equation (7) is of a local character and is defined only at strictly determined locations of the electromagnetic field. For physical analysis it is also necessary to relate the integral topological characteristics of the cells of the electric and magnetic fields. We now formulate two conditions which express the topological-integral Maxwellian relations for the schemes of the electric field e and the magnetic field h:

1. The separatrices of the cells of the schemes of the fields e and h are orthogonal with respect to one another at the points of intersection.

2. The separatrices of a closed contour of one field (e or h) are so oriented with respect to the separatrices of the other field (h or e) which intersect them that the following equality holds for the set of points of intersection:

$$\sum_{i=1}^{N} \operatorname{sign}(y_i h_i)\operatorname{sign}(x_i e_i) = 0, \tag{8}$$

where y_i and x_i are the unit vectors of a Cartesian coordinate system at the ith point of intersection.

As an example we study the topological configuration of the fields of E_{11} waves in a rectangular waveguide. The position of equilibrium of the center type for the magnetic field is located at the center of the transverse cross section of the waveguide, and saddles of the dynamical system are located at the corners. The separatrices of the field coincide with the faces of the screen. Three-dimensional saddles of the electric field lie on the central axis of the waveguide at the points $k_z z = (2n+1)\pi/2$. The separatrix connecting these saddles is located at the center of the waveguide. Four separatrices of the field e, which connect the three-dimensional saddle points with the corners, and four semiseparatrices, connecting the saddles with the centers of the metallic walls of the waveguide, also lie in the planes indicated above.

The validity of the Maxwellian topological-integral relation (8), which from the mathematical standpoint represents a special form of calculation of the index of the cell of the topological scheme for the dynamical system (6), can be easily verified by going around any closed contours of the separatrices of the fields e and h.

We now examine the application of the configurations of the fields for the physical analysis of complicated guiding structures of 3D ICs.[20] The topological approach, the principles of which were presented above, gave the key to efficient physical assessment of 3D ICs. By their very nature, the topological configuration of the fields have turned out to be robust with respect to variations of a number of parameters over their quite wide range of values. We now separate the key elements in the complicated guiding structures of 3D ICs (Fig. 5). We assume that the tangential electric fields e_t (magnetic currents on the apertures of the slots S) are given. Using the tensor Green function $\hat{g}$ the dynamical system (6) can be put into the form

$$\frac{dr_e}{dt} = e = \int_S e_t \hat{g}\, dS'. \tag{9}$$

Investigations of the systems (9) have shown the following: If e_t belongs to a definite class, for example, the class of functions whose sign does not change at the aperture, then to within the number of existing positions of equilibrium the topological configuration T_e of the field is invariant under the changes de_t. Therefore in order to obtain the topological scheme of the approximate calculation of the pattern of the lines of force it is not necessary to solve a complicated electrodynamic boundary-value problem completely. It is sufficient to know, from physical considerations, the qualitative distribution of the field e_t and the propagation constant k_z of the characteristic wave. This radically reduces the computer time required for modeling in order to investigate the basic physical properties of the characteristic waves of some types of finned-slot transmission lines for 3D ICs. The transverse cross sections of these lines with a three-dimensional arrangement of the conductors are presented on the left-hand side of Fig. 5. Reduction of radiation losses was achieved in the transmission line with fins directed toward one another (Fig. 5a); a transverse fin in a slot line made it possible to insert monolithic transistor circuits (Fig. 5b); fins at the corners of a module of a 3D IC made it possible to include powerful diode circuits near the casing for removing heat conveniently and for tuning (Fig. 5c). A line with conductors arranged in the shape of a cross (Fig. 5d) has many positive qualities: a wide band of working frequencies (even in the millimeter range) and the capability of distributing microwave power in two orthogonal planes. The functional possibilities of these lines can be significantly expanded with the help of a deep theoretical analysis and intuitive electrodynamic models which incorporate the fundamental physical information. To this end, the key elements with maximum energy concentration in the principal type of wave were chosen in the transmission lines studied (see the right-hand side of Fig. 5). The topological configuration of the field depends on the positions of the slots and fins. When the slots are positioned with an offset on opposite faces, the se-

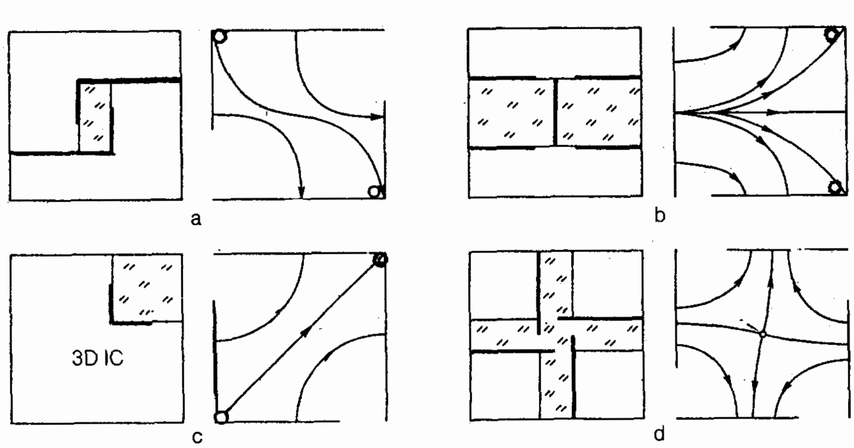

FIG. 5. Cross section and structure of the electric field of three-dimensional transmission lines. a) Finned-slot line; b) slot line with transverse fin; c) fin-corner line; d) line with cross arrangement of conductors.

paratrix (dashed line) connects two positions of equilibrium of the saddle type (circle in Fig. 5a). For a contiguous arrangement of the slots the symmetry plane is also the separatrix (Fig. 5c). The arrangement in which the slots are positioned opposite one another is characterized by two semiseparatrices, located on opposite sides of the symmetry plane (Fig. 5b). When slots are present on all faces of the waveguide there are four semiseparatrices and the position of equilibrium is located at the center (Fig. 5d). Analysis of the key structures shows that in order to describe the principal physical properties of a wave, right up to the qualitative distribution of the field, it is sufficient to determine the elements of the topological configuration. (the point of equilibrium and separatrix).[20,58,75]

The next stage in the development of the topological theory could be to establish the laws governing the formation of the topological configuration as a function of the geometric-topological properties of the boundary conditions. These laws would make it possible to take a step in the direction of obtaining a qualitative solution of the problems of determining the characteristic waves, thereby imparting to the complicated electrodynamics of microwaves the former intuitive "feel."[79] ("I want my readers to learn that the true mathematical structure of these concepts will become clear only now, as the landscape in the mountains when the fog is lifting" (A. Sommerfeld[61]).)

6. BASE ELEMENTS, FUNCTIONAL UNITS, PROCESSING DEVICES, AND INFORMATION SENSORS OF 3D MICROWAVE ICs

Thus far we have discussed primarily the problems of describing transmission lines, constructing adequate models for such lines, and so on. For the practice of circuit design, however, it is more interesting and necessary but also more difficult—c'est la vie—to work out the physics and electrodynamics of the base elements, i.e., ultimately the building blocks of 3D ICs—the module. Here we must once again point out that "one must look before leaping;" that is, without understanding the physics of the operation of an individual base element and the connections of base elements into a functional unit or module it is impossible to construct, with "little blood," a design process and ultimately a system for computer-aided design of 3D ICs. Embarking on this difficult voyage we recall the wonderful words of V. A. Fok: "The purpose of any physical theory is to obtain a picture of the phenomenon that reproduces qualitatively and quantitatively all important features of the phenomenon. This goal can be considered to have been achieved only when the solution obtained has a quite simple form. If, however, the analytical form of the exact solution is complicated, then this solution is only a first step toward the true solution of the problem; the next step must be to derive formulas suitable for numerical calculations."[32]

Analysis of the structures of 3D ICs in most cases is based on the decomposition approach, i.e., partitioning of the structure into separate elements (but mostly based elements), which can be studied quite simply (the scattering matrix S_i has been found). The general scattering matrix S is found from the matrices S_i of separate base elements in the standard manner and every computer-aided design system has the appropriate means for doing so (see, for example, Refs. 13, 30, and 35). Next the frequency characteristics are calculated from the given topology (multivariant analysis), or, conversely, the topology is calculated from the given output characteristics (parametric synthesis), depending on the engineering requirements.

We now examine some base elements and functional units that are characteristically found in 3D ICs. Most of them are novel devices, proposed and developed in our country for building information processing systems based on 3D ICs.

6.1.

The inhomogeneities consist of the connection of two transmission lines, which can have either the same or different physical properties and geometries. The case when two identical transmission lines are connected through a jump in the width of the conductor, break in the lines, and other types of inhomogeneities belongs to 2D ICs. ALthough they are an integral part of the elemental base of 3D ICs,[30,31] they have been thoroughly studied and we shall not be concerned with them.

Connections of transmission lines of different types, whose conductors are located in different dielectric layers, are complicated electrodynamic structures (Fig. 6), since in the connection plane waves of one type can be transformed into waves of a different type. In order to study them in greater detail we shall consider three-dimensional six-terminal tees, which divide the input microwave power among two outputs. The input unsymmetric strip line with a quasi-

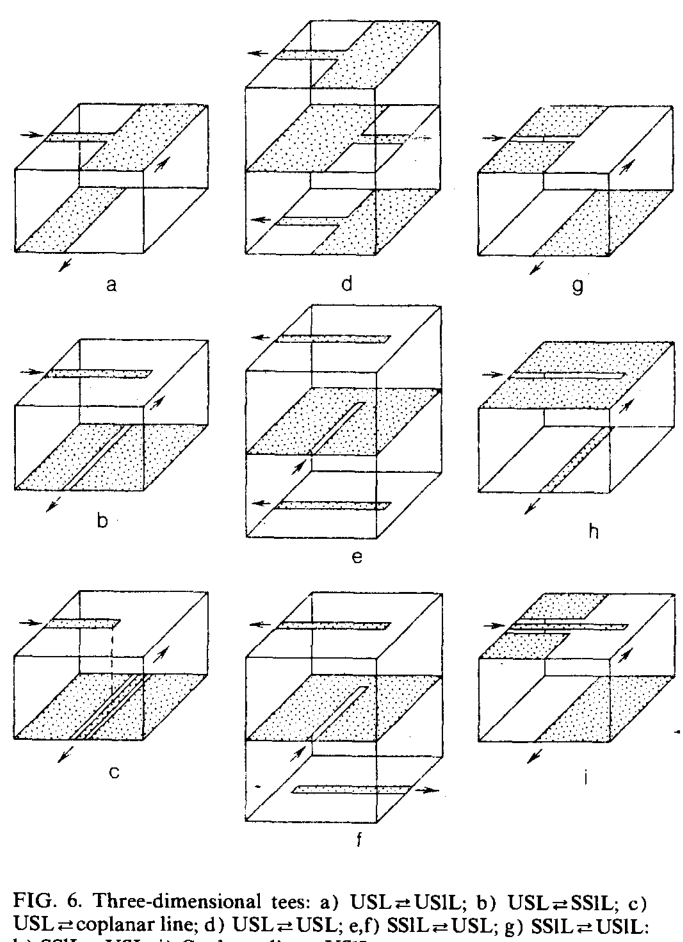

FIG. 6. Three-dimensional tees: a) USL ⇄ USIL; b) USL ⇄ SSIL; c) USL ⇄ coplanar line; d) USL ⇄ USL; e,f) SSIL ⇄ USL; g) SSIL ⇄ USIL; h) SSIL ⇄ USL; i) Coplanar line ⇄ USIL.

T-wave excites in-phase and H-wave in unsymmetric slot line (Fig. 6a) and symmetric slot line (Fig. 6b), positioned orthogonally on the opposite side of the dielectric layer, as well as a T-wave in a coplanar line (Fig. 6c).[42,81] In inhomogeneities of this type the microwave signal is transported through the dielectric layer.

When necessary the signal transport can be organized in different layers of a dielectric.[82] For example, a symmetric strip line with a T-wave excites in-phase unsymmetric strip lines, coaxially separated through a dielectric layer (Fig. 6d). The output unsymmetric strip lines can also be excited by symmetric slot lines placed between them. But here there arises the following peculiarity: Excitation is in-phase when the unsymmetric strip lines are oriented in the same direction (Fig. 6e) and is antiphase when the lines are oppositely oriented (Fig. 6f).

The connections of symmetric slot lines with unsymmetric slot lines (Fig. 6g) and unsymmetric strip lines (Fig. 6h) as well as the connections of coplanar lines with unsymmetric slot lines (Fig. 6i) are similar. In order to obtain the best matching at the region of intersection the input transmission lines are terminated with quarter-wave open or shorted segments (Fig. 6b, e, f, h, and i). A distinguishing feature of 3D tees is that the microwave signal is transported in the vertical plane, as a rule, without destroying the integrity of the dielectric layers; this greatly simplifies the fabrication technology.

The wave scattering matrices of tees, taking into account the inhomogeneities in the reference plane, are determined by the method of electrodynamic modeling with the help of different variants of Oliner's method.[82] Once models have been constructed for the different base elements, the functional units of 3D microwave ICs can be formed.

6.2.

Bridge circuits are three-dimensional directional structures, which are based on the principle of coupled arms in order to obtain in two output arms mutually decoupled signals with equal amplitudes.[83] These circuits have a great diversity of structures and physical properties. The main distinguishing feature is the shift in the phase of the signal between the output arms. Structurally, a bridge circuit is an eight-terminal network, whose arms are commutated with quarter-wave segments of a transmission line (Fig. 7). The commutating transmission-line segments can be connected in a ring circuit (ring bridge of length λ or $\lambda/2$) or with rectilinear transmission-line segments with distributed coupling via the electromagnetic field (directional coupler).

A ring bridge of length λ is made of quarter-wave segments of an unsymmetric strip line (Fig. 7a). The input branches are placed between dielectric layers while the output branches are distributed on the exterior sides.[84] The signal entering one of the input branches is divided in-phase among the output branches, while the signal entering in the other input branch is divided in anti-phase. The magnitude of the phase shift of the signal in the output branches does not depend on the frequency; this is what determines the

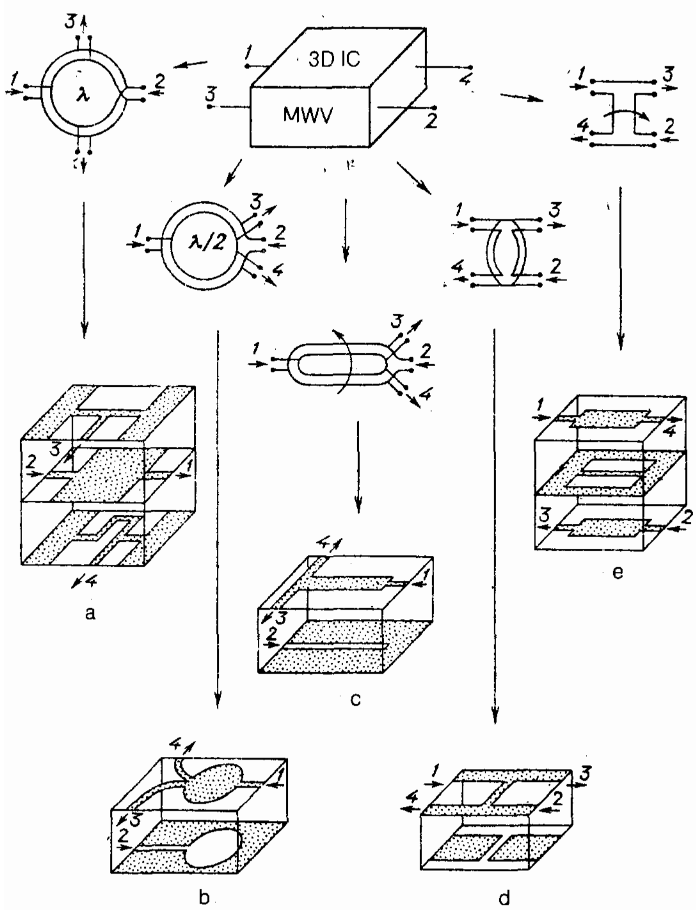

FIG. 7. Equivalent circuits and topology of 3D microwave (MWV) ICs. a) Ring bridge of length λ; b) ring bridge of length $\lambda/2$; c) magic tee; d) branch directional coupler; e) coupler based on coupled transmission lines.

high directionality (the decoupling of the input branches reaches 40 dB). The ring bridge of length $\lambda/2$ operates according to a similar principle, but the commutating transmission-line segments are made from an unsymmetric slot line (Fig. 7b).[85] Here the dimensions have been reduced, but in so doing the directionality becomes frequency-dependent (it reaches 20 dB in an octave-wide band). Losses in ring bridges do not exceed ± 0.2 dB.

The bridge circuit with coupled transmission lines on a quarter-wave segment has a different form. In-phase—antiphase division of the signal—"magic tee"—can be obtained by combining an unsymmetric strip line and a symmetric slot line (Fig. 7c).[86] Its physical properties are completely equivalent to those of the $\lambda/2$ ring bridge.

Division of a signal with a 90-deg phase shift is achieved by combining quarter-wave stubs based on an unsymmetric slot line (square branch coupler; Fig. 7d (Ref. 87)). A similar phase shift is obtained by separating the output (input) branches in different layers of a dielectric (Fig. 7e).[13] The quarter-wave region of coupling is then realized on an unsymmetric strip line with conductors of limited width; even- and odd-type waves are excited in the line. Maximum directionality is achieved when these waves have the same phase velocities.

The basic frequency characteristics of the bridge circuits studied above are determined by the coefficients of the wave-scattering matrix, which are calculated by recombining the base elements described above. Thus if the wave-scattering matrices of the base elements and functional units are known, then it is possible to study modules of 3D ICs with passive and active base elements.

6.3.

Microwave-signal processors are the principal part of radiophysical systems. They include passive devices for filtering the signal and for dividing a signal among many channels with fixed phase relations at the output. Examples of active devices are tunable phase shifters and microwave signal transducers.[88,89]

Filters consist of a collection of electromagnetically coupled cavities. The filter characteristics are made to approach the ideal characteristics—the frequency characteristic has the form of an elliptic function—by realizing a complete combination of couplings between all cavities (Fig. 8 (Ref. 90)). This approach, in the whole, cannot be realized in 2D ICs. For this, it is necessary to eliminate in the filter commutating segments of the coupling lines and go to three-dimensional types of coupling via both the electric field (break between conductors of an unsymmetric strip line)

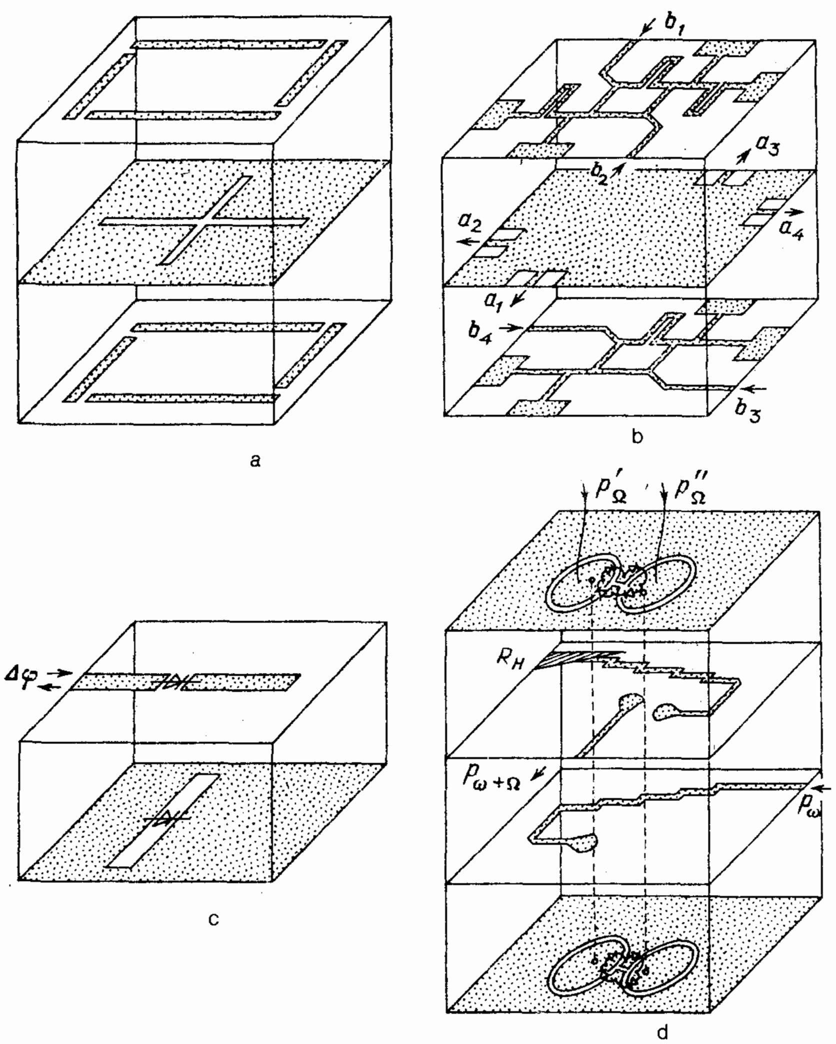

FIG. 8. Topology of functional units of 3D microwave ICs. a) Nine-cavity strip filter; b) beam-forming matrix; c) continuously tunable 360-degree phase shifter; d) microwave signal transducer.

and the magnetic field (end connection of a symmetric slot line with an unsymmetric strip line). It is evident from the topology (Fig. 8a) that the optimal types of transmission lines are chosen in order to achieve these couplings, i.e., the principle of optimality of the base elements is satisfied systematically.

Devices for feeding antenna arrays are multichannel power dividers—beam-forming matrices. The main requirement they must satisfy is that the output branches must be decoupled with a prescribed distribution of phase relations. There are many schemes for such matrices: Page, Blass, Butler, etc. As an example, we examine Page's matrix with 4×4 branches. This matrix is made by commutating in-phase and antiphase bridges (Fig. 8b).[91] In this scheme, as in other matrices, the commutating transmission-line segments must intersect with a high degree of decoupling. This is possible only in 3D ICs. For example, electric symmetry of the commutating segments of the transmission line, placed in different planes of dielectric layers, is easily achieved in the Page matrix topology (Fig. 8b); this is what leads to small imbalance of the phase of the signal ($0.180 \pm 1°$), power division (6 ± 0.2 dB), and decoupling of the branches exceeding 30 dB. The circuit design variant of this matrix, in which loss reduction and two- to three-fold expansion of the frequency band are achieved by introducing structural (strip) elements with continuously varying topological parameters, was proposed in Ref. 36.

Phase shifters of the reflection type, based on 3D ICs, have unique characteristics with respect to linear adjustment of the phase of a microwave signal. This is achieved by including varactor diodes in the reference plane without commutating transmission-line segments (Fig. 8c). The topology of the scheme is constructed according to the principle of optimality of base elements. An unsymmetric strip line is employed for series connection of the diode and a symmetric slot line is employed for parallel connection. The length of the quarter-wave shorted (symmetric slotted line) and open (unsymmetric strip line) stubs determines the working frequency of the phase shifter.

The single-band microwave signal converter is used for controlling the phase (phase manipulator), amplitude (attenuator), and frequency (frequency shifter).[14] The converter consists of two balanced modulators and two directional structures (in-phase–antiphase and square directional couplers), placed at the input and output.[92] The controlling signal is fed with a 90-degree phase shift into the input of the balanced modulators, the signal at the carrier frequency is fed into the input of the in-phase–antiphase coupler, and the processed signal is extracted from the outputs of the square coupler (Fig. 8d). These functional units are realized in the three-dimensional topology. Groups of four diodes are connected in a symmetric slot line with symmetric topology on the outer layers of the dielectric, while the topology of the passive directions of the couplers is realized in the inner layers of the dielectric. Wide bands of working frequencies (up to an octave) and suppression of the carrier frequency above 35 dB and one side frequency (above 25 dB) are achieved by excluding transmission line segments commutating the diodes, which are connected in the reference plane. Conversion losses in the frequency band are less than 5 dB.

The three-dimensional module of a single-band signal controller can, in the general case, perform an entire series of different functions, for example, amplitude and phase modulation, frequency doubling, frequency mixing, and it can also function as an amplitude, phase, and frequency detector.[93,94] In addition, in order to change the function it is sufficient to change only the form of the signals at the inputs and outputs without changing the structure of the module itself. The physical properties of the converter make it possible to digitize the signal parameters, which is very important for digital processing.

6.4.

Pickups operating individually perform measurements, while in an automatic production system they monitor completely the output of acceptable parts of a 3D IC and its basic elements. Promising devices are pickups that employ nondestructive methods for monitoring the samples investigated, where the realization and architecture of the three-dimensional interconnections via the electromagnetic field between the pickup and the sample are possible on the basis of 3D ICs. Figure 9 shows pickups measuring complex resistances (a), the dispersion characteristics of acoustic and magnetostatic waves (b), and the permittivity (c). We now briefly examine their three-dimensional construction and principle of operation.[13,14]

A device for measuring complex impedances of microwave circuits is built on the basis of an unsymmetric strip line, in whose metallization layer probes are cut in the form of unsymmetric slot lines. They are connected alternately with a detector through p–i–n diodes (Fig. 9a). The small width of the probe gaps (tens of microns) and the virtually frequency-independent coupling of the probes with the unsymmetric strip line (of the order of 15–20 dB) make the measurement accuracy significantly higher than in the case of devices based on 2D ICs. The final result of a measurement is the determination of the intensity of the field of the reflected wave and their further approximation in order to determine the phase and voltage standing wave ratio. The signal controlling the p–i–n diodes and the information-carrying signal after the detector pass through an analog-to-digital converter and are fed into a microprocessor for processing.

The physical properties of substrates with excitation of acoustic and magnetostatic waves can be investigated using sensors constructed on the basis of the principles of the design of 3D ICs (Fig. 9b). The investigation is based on the resonance method. The cavity itself is made on one side of a dielectric substrate in the form of two electromagnetic-wave interdigital transducers which are oriented opposing one another and separated by some distance. The input and output of the transducers are symmetric slot lines. In order to investigate acoustic waves a substrate, for example, consisting of lithium niobate, is applied on the resonator and in order to study magnetostatic waves an yttrium-iron garnet substrate is applied.

A resonance method, in which the resonator is made on one side of the substrate in the form of an unsymmetric strip line, formed into a ring of length $n\lambda$ (Fig. 9c), is also used for investigating the dielectric properties of substrates. The cavity is excited with a symmetric slot line placed on the opposite side. The measured substrate is applied to the resonator. The electrophysical parameters of the substrates studied are

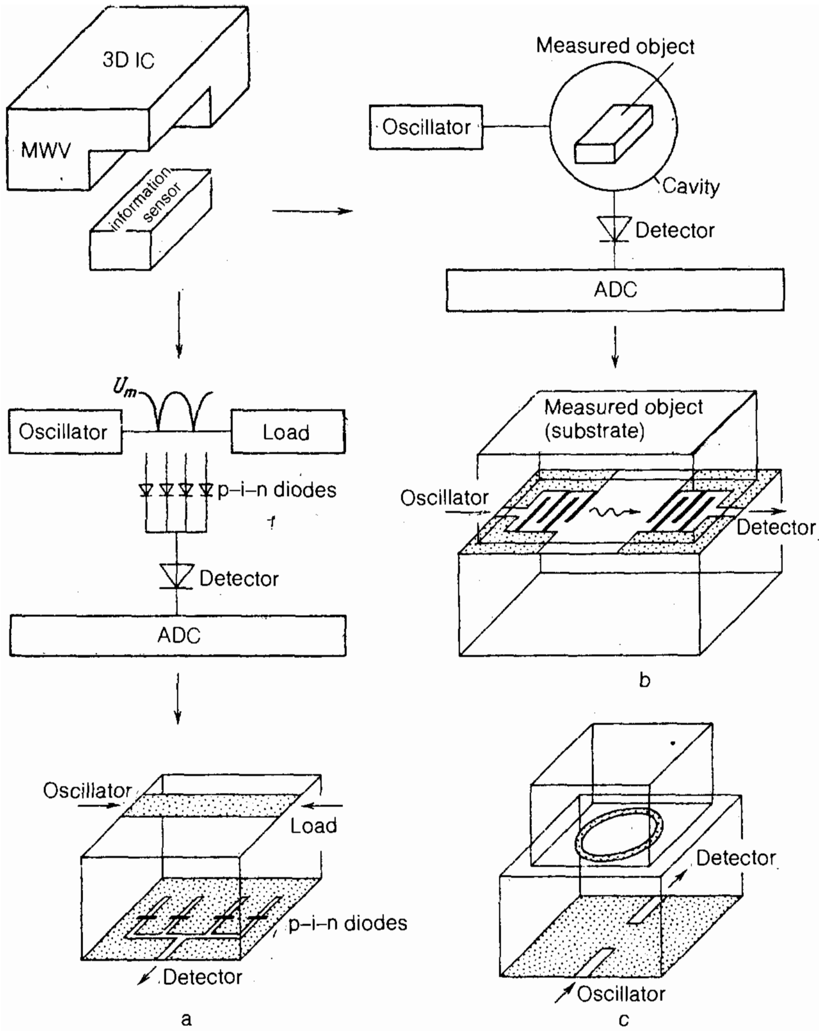

FIG. 9. Equivalent circuits and topologies of pickups of 3D microwave (MWV) ICs. a) Complex impedance meter; b) device for measuring physical properties of substrates with excitation of acoustic or magnetostatic waves; c) device for measuring the permittivity of substrates.

determined by measuring the shift in the resonance frequency recorded after the detector.

In summarizing this section, we can state that 3D ICs have been successfully incorporated into the development of a wide class of microwave devices. They are especially effective where a large number of input and output channels are formed and where unique characteristics of the electrophysical parameters must be achieved. This is achieved by eliminating a larger number of junctions and commutating lines by distributing the base elements in three dimensions. In the future, this approach can be used to create highly organized structures of 3D ICs with quite low signal power. The next stage in the development of the ideas of 3D ICs is to investigate and develop multifunctional 3D ICs, mainly with wideband transmission lines and units for processing information-carrying signals. The trend in the development of such systems is toward modular devices and devices for superfast information processing, including the EHF and radio-optical ranges.[40,60] Transmission lines and units with wide bands can be made using the existing gamut of quasiregular base elements (junctions and functional units), fabricated by hybrid, monolithic, and combined technologies.[36,40,42,44,75,93–97]

7. PHYSICOTECHNOLOGICAL ASPECTS OF 3D ICs

One of the significant advantages of 3D ICs has been the fact that industry has mastered the technologies for fabricating them. Thus 3D ICs make it possible to realize, if such an analogy is admissable, the well-known principle of Gilyarovksii's Sukharevka [market for stolen goods]: "For a farthing—fivepence!," i.e., to obtain new quality on the "old" elemental base. Examples of such jumps in technology, and especially in radio electronics, are very rare and are reminiscent, for example, of the transition to the idea and technology of digital superfast information processing systems, because the cost of the elemental base of analog processing had reached its fundamental limit.[6–10] Of course, all new technologies enter into and are suitable for future superfast information processing systems based on 3D ICs. Three-dimensional integrated circuits (for the time being, primarily, microwave), in which the technology for obtaining structures with 20 to 40 layers in a single technological process has been realized, have started to appear in the West in the last few years. Once again our technology, as could happen (and which has already happened many times before, unfortunately), will be playing catch-up, though the philosophy of 3D ICs itself, the mathematical modeling, computer-assisted design, and the first samples of superfast information processing systems were undoubtedly developed in our country.[13]

For large multifunctional 3D ICs the hybrid technology is for the time being, most suitable (our according to our criteria).[13,31,36,40,42] Even here, however, there arise additional technological problems that are peculiar to 3D ICs. In order to elucidate them we imagine an assembly of a multiplanar 3D IC consisting of several layers—substrates, on each of which are made, by thin-film technology, technological patterns, which in the three-dimensional assembly constitute the passive part of the functional unit. These substrates are assembled into a three-dimensional structure by gluing, welding, or additional mechanical binding.

In any method of assembly, because the current-carrying strip conductors have a finite thickness, gaps form between the substrates and these gaps are filled either with glue or air. The gap sizes are difficult to control, and the electrical characteristics are strongly affected by changes in the gap size. At the same time, it is virtually impossible to eliminate the air bubbles in the glue (compound) over the large area of joined surfaces. These bubbles can be eliminated by gluing or welding in vacuum chambers. The air gaps must be taken into account when designing 3D ICs, since with their "help" unsanctioned transformation of the working wave into a wave of any type, radiation, *et cetera*, can occur.

The second feature of the technological fabrication of 3D ICs is that the layers must be joined to one another very accurately. Here there arises a contradiction. On the one hand the quality indicators of 3D ICs improve exponentially with the number of layers, but on the other hand the danger of mismatching of base elements in different stages increases. This contradiction can be removed to some extent by introducing special technological operations in order to ensure high accuracy of joining. But in the case of the hybrid technology there is still a physical limit on the number of layers in a 3D IC.

The third feature of the technological fabrication of 3D ICs is the method of arranging and securing discrete active elements: diodes, transistors, bare semiconductor ICs, etc. According to the principle of optimality of base elements, transmission lines with active elements are fabricated on one side of the substrates, which are the outer layers of the dielectric; this ensures convenient cooling, screening, regulation, and maintenance (the latter, by the way, is also characteristic, unfortunately, only for our circuits). In this situation there arises a fundamental physical limit on the achievable mass-size characteristics.[16] This limitation is reduced by replacing, partially or completely, the lumped active elements with distributed active elements, which "do not extend" beyond the levels of the layers, such as traveling-wave amplifiers based on negative differential conductance in a GaAs substrate. A number of solutions to the problem of arranging active elements in 3D ICs are studied in Ref. 36 and 40.

The additional technological peculiarities listed above are eliminated by switching from hybrid to monolithic technology. Unfortunately, in our country the monolithic technology for 3D ICs has still not been developed up to the commercial level. A number of general operations, taken, for example, from the technology of monolithic 3D digital ICs (operating at frequencies of up to 100 MHz) can be employed,[19] but, on the whole, radical solutions are required. For the time being, then, it is recommended that quasimonolithic technology be employed.[23,36,40,44] In this technology the functional layer with the dielectric is made in a single technological process, after which the structure is assembled in layers. Since the cost of a monolithic 3D IC is proportional to the area of the functional layer, it is desirable to separate the functional layers with dielectric layers (substrates) with high permittivity of the order of $e_r = 40$–200. This reduces by several times the geometric dimensions of the base elements, which are multiples of a quarter wavelength. Constructions of 3D ICs of this type are examined in Ref. 36.

Experience in delving more deeply into the idea of 3D ICs and implementing this idea shows that for the modern rates of development of integrated technologies there are no insurmountable obstacles to the commercial assimilation of 3D microwave and EHF integrated circuits, including multifunctional circuits and circuits made by the monolithic (quasimonolithic) technology, not to mention the hybrid technology. The experience gained in theoretical investigations and the richness of the solutions to circuit and constructional-technological problems, only some of which are reflected here, suggests and clearly shows that we have all the prerequisites for developing commercial technology and for commercial production of the most diverse types of 3D ICs. However there is a "native" paradox: in spite of the obvious advantages of 3D ICs over 2D ICs (greater reliability, higher resistance to external factors, sharp decrease in mass and size, etc.), large-scale production of 3D ICs is hindered, as it is customarily said in our country, by bureaucratic lack of cooperation. Enterprises which require 3D ICs do not yet have the needed technology, while organizations which do have the corresponding technology do not need 3D ICs. Personality factors and subjectivism play a large role in this regression. Even with all this, the "resistance" to a new idea is natural, dialectical, and it could be justified using the theory of measures of innovation and Godel's theorem from logic.[26,40] This is still another reason for optimism, though it is difficult to forget the well-known arguments of P. L. Kapitsa concerning the problems of adoption of new achievements in technology.[99]

8. CONCLUSIONS

Thus 3D ICs are one of the last—in our case, last in time—steps in the development of microelectronics. As in any science, new achievements and discoveries are recognized as being revolutionary if the last step is a chain reaction of publications in our and the foreign literature. Something like this has happened with 3D ICs. In our country it is increasingly believed that "For electronics of the future, in particular, for computers of future generations...integrated circuits of a new type are being developed—3D ICs,...reminiscent of a layer cake,...each layer of which is a familiar planar IC."[100] The formulated physical principles of 3D ICs give designers a promising and tested apparatus and its technological implementation in the SHF range, which make it possible to solve the problem of interelement and interunit connections,[101–104] i.e., ultimately the famous "problem of conductors," by making electromagnetic interlevel couplings instead of galvanic connections.

In the industrially developed foreign countries it is now firmly believed that planar ICs will reach their limiting packing density at the beginning of 1990's, after which further improvement of the packing density as well as expansion of the functions will depend on progress in vertical-integration technology—the development of 3D ICs. The technology of 3D ICs is based on the fabrication of layers by the "silicon-on-dielectric" technology followed by monolithic superposition of the layers.[19] "Layered semiconductor structures of the type insulator-semiconductor, which, if interlayer connections with a definite configuration can be fabricated, will become the basis of truly three-dimensional 3D microwave ICs."[102]

A striking manifestation of the technical advantages of 3D ICs up to now are probably the above-mentioned beam-forming matrices for feeding phased antenna arrays, where the sizes and masses have been reduced by one to two orders of magnitude, and devices for digitizing and controlling microwave signals, where the working-frequency band has been expanded by several times.[14] In view of the high efficiency of 3D ICs a committee for investigation of 3D ICs, headed by MITI,[19] has been created in Japan. In the USA there are least 10 laboratories and firms developing models of propagation of electromagnetic waves in complicated three-dimensional structures of the type metal-semiconductor—insulator; funding is provided by the Department of Defense and the U.S. Air Force as well as by the National Science Foundation.[103]

In concluding this paper, we underscore the fact that three-dimensional microwave circuits require a new theoretical approach. Particularly acute is the issue of adding to the arsenal employed by investigators and designers an understanding of the physics of the formation of three-dimensional vector fields in complicated media and the relation of the field and topological characteristics to the integral parameters (wave numbers and scattering matrices).[71,105] The effectiveness of promising 3D ICs, realized with modern technological methods for making microwave and EHF super fast information processing systems, depends on how quickly progress can be made in developing the topological electrodynamics of three-dimensional integrated circuits.

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