NEW INSTRUMENTS AND MEASUREMENT METHODS

Quantum amplifiers and their application in space research

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Principles of design and construction are described for modern quantum amplifiers (masers), which are the most sensitive input devices of ultrahigh-frequency radio receiving systems. Data are given on the characteristics of paramagnetic crystals for quantum amplifiers (QA) and on the attained QA parameters. Problems are discussed of application of QA in radio astronomy (cosmic radiospectroscopy, radar observation of planets, very-long-baseline radiointerferometry, etc.) and in long-range space radio communication systems.

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CONTENTS

1. INTRODUCTION

Improvement of sensitivity of radio reception has always been one of the fundamental problems of radio electronics. The urgency and topicality of this problem increased considerably in the sixties in connection with the onset of active study and mastery of outer space.

At that time in the microwave region[1]—the fundamental wavelength region for studying outer space by radio methods—the best input radio receiving devices with respect to noise characteristics were considered to be crystalline semiconductor mixers with a noise temperature[2] of 1000–2000 °K. Subsequently, it has been possible to diminish substantially the noise temperature of radio receivers in the microwave range through development of a series of new input low-noise devices (electronic microwave amplifiers; parametric, tunnel, and transistor amplifiers; quantum amplifiers).

Among the low-noise devices in the microwave range, quantum amplifiers, or as they are often called, masers, occupy a special place: they have the lowest intrinsic noise and are a kind of a standard. The degree of approximation to which can characterize the noise properties of other types of low-noise devices.

The noise temperature of quantum amplifiers is extremely low—only about 10 °K. Hence they are used whenever the main requirement imposed on a radio receiving system is to ensure the lowest possible noise temperature.

This is just the type of system that includes the Earth-based radio-receiving long-range space communication (LRSC) systems and a number of radioastronomical systems (spectral radiometers, very-long-baseline radiointerferometers, planetary radar, etc.).

The operation of quantum amplifiers is based on using the stimulated emission of radiation by nonequilibrium quantum systems having an inverted population of energy level ("active" systems).

The fundamental method of getting an inverted population in such systems is the "pumping" method proposed by Basov and Prokhorov.[1] In this method a system of particles possessing three energy levels $E_1 < E_2 < E_3$ is subjected to an auxiliary electromagnetic radiation (the pump) having a frequency that corresponds to the quantum transition between the outer members of the three levels (E_1 and E_3). With a strong enough pump, this transition is saturated (the populations of the levels E_1 and E_3 become the same) and the population of one of the upper levels (E_3 or E_2) comes to exceed that of a lower-lying level. This is called an inversion of populations.

The active material in quantum amplifiers consists of dielectric crystals isomorphously doped with paramagnetic ions that possess a suitable system of three (or more) energy levels. The spacing between the levels, which can be regulated by imposing an external magnet-

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[1] Conventionally one assigns decimeter, centimeter, and millimeter wavelengths to the microwave region.

[2] The noise properties of a receiving device are customarily characterized by the noise temperature T. This is the temperature of an absolutely black body measured in degrees Kelvin equivalent to an antenna whose thermal radiation produces noise in the receiver equal in intensity to the intrinsic noise of the latter.

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ic field, correspond to quantum transitions in the radio range.[2,3] In order to get inverted populations that ensure effective operator of the amplifier, the paramagnetic crystal must be kept at a low enough temperature, as a rule, at liquid-helium temperature.

The first studies in the quantum-amplifier field were mainly concerned with studying the new amplification principle and the physical phenomena associated with it. At the same time it was necessary to find out how to design devices having the required high parameters for practical application (high gain, extremely low noise, broad enough passband, high stability and reliability, etc.) on the basis of the formulated general principles. In order to do this, systematic studies were carried out in a number of countries (mainly the USSR and USA), with resultant design of quantum amplifiers (QA) over a broad range of wavelengths—decimeter to millimeter—that possessed the needed characteristics. In the course of these studies, paramagnetic crystals for QA were investigated, methods were developed for building efficient amplifiers of this type, reliable QA were designed for different ranges of wavelengths, and were manufactured commercially. At the same time methods of coupling QA to large antennas were developed and introduced into practice that enable one to realize the potentialities of QA in enhancing the sensitivity of radio receiving systems.

Currently QA are being successfully applied in deep-space communication systems, in the largest radio telescopes, and in planetary radar ensuring maximally high sensitivity of these systems.

This review will briefly cover the fundamental results of the studies (mainly in the USSR) in the field of quantum amplifiers; will describe the design and characteristics of modern QAs,3) and will present the fundamental information on their application in space studies and on the scientific results obtained thereby.

2. PARAMAGNETIC CRYSTALS FOR QUANTUM AMPLIFIERS

As we have noted above, doped paramagnetic crystals are used as the amplifying (active) material in QA. This is the term applied to crystals that have paramagnetic ions of elements belonging to one of the transition groups of the Mendeleev periodic system isomorphously implanted as a small admixture (hundredths of a percent) into a lattice consisting of diamagnetic ions.

One can characterize the efficiency of a paramagnetic crystal in an amplification regime by the quantity χ'', which is the imaginary component of the complex magnetic susceptibility at the frequency f of the signal to be amplified (for more details, see Sec. 3). We can express the quantity χ'' by the relationship[4-6;] 4)

$$\chi'' \approx 10^{-13} (N_1 - N_2) \frac{\sigma^2}{\Delta\nu}; \qquad (2.1)$$

Here N_1 and N_2 (cm^{-3}) are respectively the populations of the lower and upper energy levels between which the transition occurs at the signal frequency; $\Delta\nu$(Hz) is the width of the electron paramagnetic resonance (EPR) line at the signal frequency (its shape is assumed to be Lorentzian); and σ is the dimensionless "effective" matrix element that determines the probability of stimulated quantum transitions at the signal frequency (it is calculated from the known matrix elements of the spin operator taking into account the direction and polarization of the UHF magnetic field of the signal acting on the particle). We note that we have $\sigma^2 = \frac{1}{2}$ for pure spin states corresponding to the spin value $\frac{1}{2}$ with circular polarization of the UHF magnetic field in a plane perpendicular to the applied external dc magnetic field.

In population inversion, which the pump (auxiliary radiation) makes attainable, we have $N_1 < N_2$. Here the quantity χ'' is negative, which leads to amplification of an electromagnetic wave of frequency f upon interacting with the paramagnetic crystal.

The difference $N_1 - N_2$ of populations of particles is customarily expressed in terms of the population difference in thermal (Boltzmann) equilibrium $(N_1 - N_2)_B$ and the so-called inversion coefficient J:

$$(N_1 - N_2) = -J\,(N_1 - N_2)_B \,. \qquad (2.2)$$

The inversion coefficient J, which characterizes the efficiency of action of the pump, depends on the ratio of frequencies of the pump and the signal, increasing as this ratio increases. It also depends on the relative values of the probabilities of radiationless (relaxation) transitions between the levels. One can express it in terms of these quantities by analyzing the kinetic equations for the populations of the system of levels being studied.[2-6] In a QA in the microwave range, the populations of the levels differ insignificantly, and the following approximate formula holds for χ'':

$$|\chi''| \approx 10^{-13} J \frac{N}{n} \frac{hf}{kT} \frac{\sigma^2}{\Delta\nu}; \qquad (2.3)$$

Here N is the total number of paramagnetic ions per cm^3, n is the total number of levels in the ground state of the ion, h is Planck's constant, k is Boltzmann's constant, and T is the absolute temperature. The efficiency of a paramagnetic crystal in a quantum amplifier increases with increasing absolute value of χ'' (see Sec. 3). Therefore the active crystal is cooled to liquid-helium temperature to attain the values of χ'' required in QA. However, we note that the value of χ'' is small, usually being of the order of 10^{-3}, even at liquid-helium temperature in the paramagnetic crystals used in QA.

In order for some particular paramagnetic crystal to be effectively applied in quantum amplifiers, it should satisfy a number of specific and at times contradictory requirements.

First of all, as we pointed out above, the doping paramagnetic ion in the crystal should possess in the ground state a system of three or more energy levels. The

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3) We present information only on the QA currently in use. One can find data on the numerous laboratory QA or on those not currently in use in the journal articles cited in the bibliographies of Refs. 4–6.

4) The formula is written in the CGS system.

splittings between them should allow one to amplify signals of a given frequency with a pump frequency lying in a suitable (technically mastered) range. The doping paramagnetic ion in the crystal is affected by the internal electric field created by the environment.[7-8] This field splits the electronic energy levels. The size of the splitting depends on the strength and the symmetry of the field. One can "adjust" the splittings of the intracrystalline field (they are usually called the "initial" splittings) to the desired values by additionally subjecting the ion to an external magnetic field. The latter gives rise to Zeeman splitting and shift of the levels that depend on the strength of the applied external magnetic field and on it orientation with respect to the symmetry axes of the internal field of the crystal.

The choice of the active material also involves the values of the matrix elements of the transitions at the signal and pump frequencies. The matrix element of the signal transition determines the efficiency of the active material [see (2.1)]. Therefore one usually employs for amplifying a signal a well "allowed" transition having a matrix element σ close to unity. Here the value of the matrix element of the pump transition should not be too small, since it determines the required power of the pump generator.

The requirements imposed on such an important characteristic of the doping ion in the crystal as its spin-lattice relaxation time T_1 are highly contradictory.[5-8] The value of T_1 depends on the temperature T (increasing with declining T) and on the concentration of paramagnetic ions, and generally it differs for different transitions. The lower T_1 is, the greater the power that is needed to saturate the pump transition. Yet an excessively large value of T_1 diminishes the dynamic range of amplifiable signals and lowers the maximum signal power that can be amplified without nonlinear distortions (see Sec. 3).

The attainment of suitable values of T_1 is another reason why one must cool the paramagnetic cyrstals to low enough temperatures. The value of T_1 in the crystals applied in QA usually lies in the range 10^{-3}–10^{-1} sec.

An important parameter of an active crystal is the value of the inversion coefficient J attainable in an amplification regime,[3-6] which one always tries to make as large as possible. Usually in the known QA the value of J in the active crystal lies in the range from unity to several times that value.

Definite requirements are imposed on the EPR line of the active crystal. Usually in crystals for QA the line width lies in the range 50–100 MHz.

Of practical importance also are such requirements on the active crystals as their stability to various physicochemical agents, a low level of dielectric losses, and existence of a developed technology of their preparation.

The development of QA in the radio range was based on studies of paramagnetic crystals and the interrelation of their properties with the characteristics of QA. The results of these studies are given in a series of reviews and monographs.[3,5-9]

We note that, prior to the invention of the first QA in studies of the EPR phenomenon discovered by E. K. Zavoĭskiĭ in the USSR in 1944,[10] studies on resonance spectra predominated, while the scope of the studies of relaxational properties was rather restricted. The problems that arose with the invention of the first QA led to an expansion of studies of EPR spectra in doped paramagnetic crystals, but to an even greater degree they stimulated the study of relaxation processes. This led to considerable progress in development of this branch of solid-state physics.[7,8]

In particular, the studies in the QA field stimulated experimental and theoretical studies of processes of establishement of equilibrium within a spin system and of the role of the spin-spin interactions in these processes. The need to explain a number of new experimental facts led to the discovery of the phenomenon of spin-spin cross-relaxation.[11] Cross-relaxation couples transitions having different probabilities of spin-lattice relaxation and alters the relationship between the rates of relaxation between different pairs of levels, and thus affects the value of the inversion coefficient J. The phenomenon of cross-relaxation has permitted us to understand why there is a limit to the increase in the absolute value of the inversion susceptibility χ'' with increasing concentration of paramagnetic ions in the crystal. As the concentration increases, the role increases of multispin cross-relaxation transitions and the regions of action of the individual processes overlap. Cross-relaxation gradually takes over all the transitions, and saturation of any of them causes all the rest of the transitions to saturate to some extent ("common cross-relaxation"). Consequently the inversion coefficient J begins to decline with further increase in the concentration of active ions. Thus there is a certain temperature-dependent optimal concentration at which the absolute value of χ'' reaches a maximum.

The requirements on the active crystals impose rather rigid restrictions on their characteristics. Hence it is not fortuitous that only a few of the large number of studied crystals have proved suitable for designing QA that have found practical application.

In the known crystals for QA, the active ions are doping ions that belong to the iron transition group and the rare earths, with most of the QA described in the literature being based on ions of the iron group, namely the Cr^{3+} and Fe^{3+} ions.

Among all the known active crystals, ruby occupies an exclusive place, and has been employed in the overwhelming majority of QA that have enjoyed practical application in modern radio systems.

It is well known that ruby is one of the crystal modifications of aluminum oxide (Al_2O_3) termed α-corundum, in which a small fraction of the Al^{3+} ions has been isomorphously replaced with Cr^{3+} ions. Data on the EPR spectrum of the Cr^{3+} ion in ruby and its theoretical interpretation first appeared in Ref. 12.

Ruby has proved to be the most suitable active material in QA of various types and uses for a number of reasons. The initial splitting of the ground quadruplet level of the Cr^{3+} ion into two Kramers doublets, which is caused by the joint action of the trigonally symmetric intracrystalline field and of spin-orbital coupling, lies in the centimeter wavelength range (it equals 11.5 GHz). A system of four energy levels is produced upon applying an external magnetic field. By varying the angle between the trigonal axis of the crystal and the direction of the magnetic field, as well as the strength of the latter, one can get a large selection of variants for amplifying signals having wavelenths lying in the decimeter, centimeter, and long millimeter ranges. Here the pump frequency lies in accessible ranges, while the value of the external magnetic field proves moderate. Ruby has a good combination of suitable values of the matrix elements, relaxation time, width of EPR line, and outstanding mechanical and dielectric characteristics (see, e.g., Refs. 3, 6).

Among the other active crystals that have been studied, most attention has been paid to rutile (one of the crystal modifications of titanium oxide, TiO_2) doped with Cr^{3+} or Fe^{3+} ions and also to corundum doped with Fe^{3+} ions.

Owing to a considerable initial splitting of the energy levels, doped rutile crystals allow one to increase the ratio of the pump frequency to the signal frequency and to get a larger value of the inversion coefficients J ($J > 10$) for designing QA in the 1–6 GHz range.

The doping Fe^{3+} ion makes it possible in principle to design a QA without applying an external magnetic field and to employ the active material in this case in the form of a polycrystal or powder.

We should especially mention such crystals as beryl ($Al_2Be_3Si_6O_{18}$) doped with Cr^{3+} ions (emerald) and andalusite (Al_2SiO_5) doped with Fe^{3+} ions. While favorably differing from ruby in their considerably greater initial energy-level splittings (the total initial splitting for emerald is 53.6 GHz, while in andalusite it amounts to almost 350 GHz), they also have acceptable relaxation times. In these crystals one can attain increased inversion values at lower magnetic fields (see, e.g., Refs. 13–15), and also get large values of the matrix elements of the transitions, both at the frequency of the signal to be amplified and at the pump frequency.

Unfortunately, synthesis of andalusite has not yet been worked out. We can hope that progress is preparing artificial emerald crystals will permit us in the near future to design efficient QA based on this crystal in the millimeter wavelength range.

Table I gives the parameters of the above-cited crystals for QA.

One can find a more complete and detailed treatment of crystals for QA, e.g., in Refs. 3, 5, and 6.

We shall illustrate on the example of ruby how one employs the energy levels of the active ion in a QA.

TABLE I. Active crystals for quantum amplifiers.

Crystal	Dopant ion	Dopant concentration, %	Initial splittings of levels, GHz	Typical values of the time T_1 (msec) at 4.2°K
Al_2O_3 (corundum)	Cr^{3+} Fe^{3+}	0.03–0.04 0.02–0.05	11.47 $\Delta_1 = 12.05$ $\Delta_2 = 19.3$	10^2–10 10–1
TiO_2 (rutile)	Cr^{3+} Fe^{3+}	0.01–0.04 0.01–0.04	43.3 $\Delta_1 = 43.3$ $\Delta_2 = 81.3$	1 1
$Al_2Be_3Si_6O_{18}$ (beryl)	Cr^{3+}	<0.1	53.6	10–1
Al_2SiO_5 (andalusite)	Fe^{3+}	0.07	$\Delta_1 = 116.1$ $\Delta_2 = 232.2$	1

For the Cr^{3+} ion, the splitting is indicated of the ground spin quadruplet into two Kramers doublets by the intracrystalline field. For the Fe^{3+} ion, the ground spin sextet is split in the crystal field into three Kramers doublets; the splittings are indicated between the two pairs of adjacent doublets.

The relative arrangement of the energy levels of the doping chromium ions is determined by the strength of the external magnetic field and by the angle θ between the directions of this field and of the trigonal symmetry axis of the intracrystalline electric field. In zero magnetic field, the employed group of levels (four spin sublevels of the ground orbital singlet) consists of two Kramers spin doublets with an initial splitting between them of 11.5 GHz. When an external magnetic field is applied, splitting of the spin doublets takes place, and its relationship to the value of the applied magnetic field differs for difference angles θ. Figure 1 shows the relationship of the positions of the energy levels to the strength of the applied field for the two most commonly used cases $\theta = 54°44'$ and $\theta = 90°$.

When $\theta = 54°44'$, the relationship of the level splitting to the value of the field proves to be symmetric with respect to the horizontal axis. The minimum spacing between the middle levels 2 and 3 (the transition between them is commonly used for amplifying the received signal) is half the initial splitting. This determines the minimum possible frequency of amplifiable signals in the given variant. For pumping, here one uses simultaneously the two transitions of equal frequency 1–3 and 2–4. This double pump allows an appreciable gain in the inversion coefficient as compared with using only one transition for pumping.[3-6]

As a rule, the variant with $\theta = 90°$ is used for lower

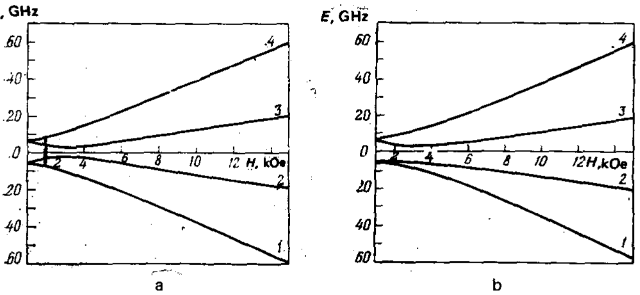

FIG. 1. Energy levels in ruby. a) $\theta = 54°44'$; b) $\theta = 90°$.

amplifiable frequencies. An important advantage of this variant is that the angular dependence of the EPR spectrum is minimal here, and the scatter in real ruby crystals in the direction of the axis of the intracrystalline field for the individual ions does not lead to appreciable broadening of the EPR lines nor to a concomitant decline in amplification. One usually employs the transition 1–2 for amplifying the signal in this regime. One uses the transition 1–3 as the pump in amplifiers for the decimeter range of wavelengths; in amplifiers for the centimeter range one gets a greater inversion by using the transition 1–4 as the pump. A regime has also been studied that involves simultaneous pumping by the transitions 1–3 and 3–4, which is distinguished by requiring a smaller pumping power than when the transition 1–4 is used.[6]

3. CONSTRUCTION AND CHARACTERISTICS OF MODERN QUANTUM AMPLIFIERS

In principle one can get quantum amplification by passing the electromagnetic wave to be amplified through an ordinary waveguide filled with an active material. However, owing to the low value of the inversion magnetic susceptibility of the crystal (see Sec. 2), attaining an appreciable amplification would require using active crystals several meters long, which is practically unrealizable.

Therefore, in the first experimental apparatus to study the effect of quantum amplification in paramagnetic crystals, arrangements were made for the wave being amplified to interact with the crystal in a volume resonator. In this case the electromagnetic wave interacts with the active material for a prolonged time upon being multiply reflected from the walls inside the resonator. This permits a large amplification with relatively small dimensions of the crystal.

The power amplification coefficient G and the band Δf of amplifiable frequencies (at the 0.5 level) of a resonator QA built according to the so-called reflection scheme (in this scheme the wave to be amplified and the amplified wave pass through the same waveguide, and are separated by using a nonreciprocal device; a ferrite circulator) satisfy the following approximate relationship (for more details see Refs. 3–6):

$$(\sqrt{G}-1)\,\Delta f \approx \frac{2d_m f}{1+(d_m f/\Delta\nu)}; \tag{3.1}$$

Here $\Delta\nu$ is the width of the EPR line; f is the signal frequency; d_m is the modulus of the negative magnetic decrement, which characterizes the efficiency of interaction of the active paramagnetic substance with the high-frequency magnetic field in the resonator (for brevity, d_m is called simply the magnetic decrement).

The value of d_m is determined by the following formula (in the CGS system):

$$d_m = 4\pi\,|\chi''_{\max}|\,\eta. \tag{3.2}$$

Here $\chi''_{\max}$ is the magnetic susceptibility for the maximum possible value of the effective matrix element σ [see Eq. (2.1)]; η is the so-called filling factor, which characterizes the extent of filling of the resonator with the active material and also the deviation of the direction and polarization of the magnetic field in the resonator from the optimal conditions at which σ reaches its maximum possible value.

The existence in Eq. (3.1) of the invariant $(\sqrt{G}-1)\Delta f$ causes a marked narrowing of the band of the amplifier with increase in amplification. This involves the regenerative nature of the amplification in a resonator QA and is characteristic of regenerative amplifiers of any type.

Here the amplification coefficient G of the regenerative amplifier is determined by the formula

$$G \approx \left(\frac{1+\beta}{1-\beta}\right)^2. \tag{3.3}$$

Here β is the regeneration parameter, which equals the ratio of the modulus of the negative decrement of the active material in the resonator to the damping decrement arising from coupling of the resonator to the external circuits, together with losses in the resonator itself.

The QA having a single resonator that were used in the initial period had substantial defects inherent in regenerative devices: in order to attain the needed large amplification coefficient, one had to apply a large degree of regeneration ($\beta \approx 1$). Such QA are unstable [see (3.3)] and they amplify only in a very narrow band of frequencies which doesn't suffice for most practical applications. For this reason single-resonator QA are not used currently in practical radio receiving systems.

The above-cited defects of QA were eliminated in two ways in parallel. In one of these, QA were developed having several intercoupled resonators—active (i.e., filled with an active material) or passive (empty). The other way consisted in producing and perfecting practically nonregenerative QA: traveling-wave quantum amplifiers (TWQA).

A number of investigators have proposed,[16] analyzed theoretically[16–18] and built[19–22] QA that employ several coupled active resonators in one-stage and two-stage designs. These multiresonator amplifiers have a greater band width for the same total number of resonators than amplifiers that employ combinations of active and passive resonators,[23] since the band width of a multiresonator QA is proportional in the first approximation to the number of active resonators.[6,21]

Multiresonator QA are currently applied mainly in the decimeter wavelength range. Figure 2 shows the

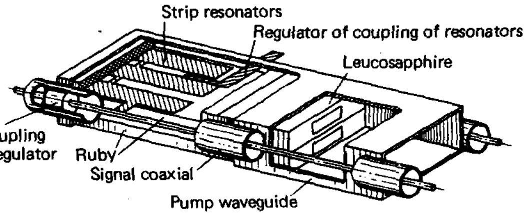

FIG. 2. Resonator system of a quantum amplifier for the decimeter wavelength range.

resonator system of a two-state QA for the decimeter wavelength range.[22] Each state uses three active resonators coupled in pairs. The stages are connected to external circuits and to one another by using a small-dimension ferrite circulator that operates at liquid-helium temperature. The parameters of the amplifier are given in Table II (cf. p. 858).

In the centimeter and millimeter wavelength ranges, the main type of QA, which has enjoyed practical application in functioning radio receiving systems, is the TWQA. In these amplifiers the traveling wave of the signal is amplified while propagating in a waveguide of special type: a slow-wave system (SWS), filled with an active paramagnetic crystal. The application of waveguide SWS in which the group velocity v_{gr} of the wave is many times smaller than the velocity c of propagation of the wave in free space makes it possible to shorten to an acceptable value the length of crystal required for obtaining a large amplification coefficient of the TWQA.

An important feature of the TWQA is that regeneration effects in these amplifiers are practically fully suppressed by absorption of the backward-traveling wave by special nonreciprocal ferrite absorbers placed inside the SWS (internal decoupling). This makes the amplifier insensitive to mismatch of the input and output impedances. Owing to the nonregenerative nature of the amplification, the stability of amplification and the passband of a TWQA with large amplification prove to be considerable greater than in a resonator QA. Moreover, one can achieve in a TWQA a rapid electronic tuning of the frequency by simultaneously changing the strength of the d.c. magnetic field and the pump frequency.

The amplification coefficient G of a TWQA as expressed in decibels $[G_{(\mathrm{db})}]$ is determined by the following relationship[3-6]:

$$G_{(\mathrm{db})}=G_{l,(\mathrm{db})}-L_{(\mathrm{db})}=27.3\frac{c}{v_{\mathrm{gr}}}\frac{l}{\lambda}d_m-L_{(\mathrm{db})}. \tag{3.4}$$

Here $G_{l,(\mathrm{db})}$ is the amplification (in db) without accounting for losses in the SWS, $L_{(\mathrm{db})}$ is the losses in the SWS (in db), l is the length of the crystal in the SWS, λ is the wavelength in free space, and d_m is the magnetic decrement of the active crystal.

With typical values of d_m of the order of 10^{-2} and a value of l/λ in the range from ~1 to ~5 (depending on the wavelength range), one requires a retardation coefficient c/v_{gr} of the wave from 50 to 200 in order to get the required amplification coefficient of the TWQA $G_{(\mathrm{db})}=25-30$ db.

The passband of the TWQA (at the 3-db level) is determined by the formula:

$$\Delta f=\Delta\nu\cdot\sqrt{\frac{3}{G_{l,(\mathrm{db})}-3}}. \tag{3.5}$$

A typical value for TWQAs is $\Delta f=20-30$ MHz, which is considerably larger than in resonator QA. One can get an even greater band expansion Δf in TWQA by applying a magnetic field whose intensity varies from point to point along the crystal situated in the SWS causing corresponding changes in the EPR frequency.[4,6,24] By such a method a value $\Delta f=150$ MHz has been realized in a TWQA.

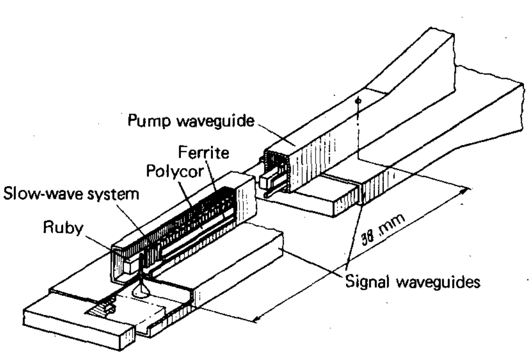

FIG. 3. Design principle of the high-frequency portion of a traveling-wave quantum amplifier for the 0.8-cm wavelength range.

One can achieve a retardation of the group velocity of an electromagnetic wave by increasing the dielectric permittivity of the medium inside the waveguide or by employing systems having frequency dispersion. One can get a greater retardation in the latter. The different types of SWS have been studied in detail, both theoretically and experimentally.[6] Highly efficient comb SWS for TWQA in the centimeter and millimeter wavelength ranges have been developed on the basis of these studies.

Figure 3 shows the design of the high-frequency unit of a TWQA for the wavelength range 0.8 cm.[6,25] This amplifier employs a comb slow-wave system situated in the pump waveguide. On one side of the pins is the paramagnetic crystal—a thin ruby bar (transverse dimension ~0.75 mm, length ~40 mm), and on the other, a thin Polycor[5)] plate whose cross-sectional dimensions have been chosen to obtain the needed dispersion characteristic that yields the required group-velocity retardation (in the described TWQA this is about 50). Alongside this plate, a ferrite rectifier is placed on a dielectric base along the entire slow-wave system in the form of a long bar of polycrystalline yttrium iron garnet. The ferrite lies in the region of the SWS where the UHF magnetic field is almost circularly polarized. This enables one to obtain good characteristics of the rectifier (damping of the backward wave by no less than 75 db with losses in the forward direction of about 2.5 db).

Table II gives the parameters of some TWQA in the 8-mm wavelength range.

The noise temperature is the most important parameter of the input radio receiver of an instrument for the microwave range.

A number of studies[4,26,27] have analyzed the problem of the limiting sensitivity of receivers of electromagnetic radiation. In particular, they have shown[26] from Heisenberg's uncertainty principle that the limiting minimal noise temperature $T_{\min}$ is determined by the following formula for a linear coherent amplifier, i.e.,

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[5)] Polycor is a ceramic prepared from polycrystalline corundum powder.

TABLE II. Parameters of some quantum amplifiers applied in LRSC systems and in radioastronomy.

Wave-length range, cm	Amplification coefficient, db	Passband, MHz	Tunable band, MHz	Noise temperature, °K	Paramagnetic crystal	Country	Remarks
30	23	15		6	Ruby	USSR	2 stages of 3 coupled resonators each
30	30	3.5	70	6	Rutile (Cr^{3+})	Sweden	Crystal temperature 2°K
17	32	4.5	200	6	Rutile (Fe^{3+})	»	
12	27—45	10	180	6	Ruby	USA	
5	30	30	250	10	»	USSR	
5	24	20	850	10	Rutile (Fe^{3+})	Sweden	
3.5	45	17—20	100	10	Ruby	USA	
3.5	25	20	700		Rutile (Fe^{3+})	Sweden	Crystal temperature 1.7°K
2	30—45	17	2000	13	Ruby	USA	
1.3	30—40	30	2000	20	»	USSR	
0.8	25—30	25	2000	20	»	»	

an amplifier in which the phase of the oscillation to be amplified is conserved apart from an additive constant:

$$T_{\min}=\frac{1}{\ln 2}\frac{hf}{k} \tag{3.6}$$

(notation explained above).

Such an amplifier is termed ideal.

In the radiofrequency range $T_{\min}$ is extremely small; thus, for example, $T_{\min}\approx 0.7°$ K in the 3-cm wavelength range.

The noise temperature of a quantum amplifier is approximately equal to the limiting value of $T_{\min}$ whenever the population of the lower energy level of the quantum transition at the signal frequency is much smaller than for the upper level. Yet actually in a QA for the radio range, the populations of the energy levels differ insignificantly from one another, and the noise temperature proves to be different from $T_{\min}$.

For a TWQA in the radiofrequency range, the noise temperature directly at the input of the slow-wave system ($T_{\rm SWS}$) is determined by the following approximate formula[4-6]:

$$T_{\rm SWS}\approx\frac{T}{J}\,\frac{G({\rm db})+L({\rm db})}{G({\rm db})}+T\,\frac{L({\rm db})}{G({\rm db})}\,. \tag{3.7}$$

Here T is the temperature of the paramagnetic crystal and J is the inversion coefficient (see above for the rest of the notation).

The first term in (3.7) arises from spontaneous emission, and the second from Joule losses in the SWS. With typical parameters of the TWQA, the noise temperature $T_{\rm SWS}$ amounts to about 3° K. That is, it differs but little from the limiting value $T_{\min}$.

Owing to the unavoidable losses in the input waveguide that connects the QA input to the SWS, the noise temperature $T_{n,\rm QA}$ of the entire QA is usually several times as large at $T_{\rm SWS}$.

For the centimeter wavelength range $T_{n,\rm QA}$ amounts to 5–10° K, and to about 20° K in the millimeter range.

One of the characteristics of QA is the maximum power of the output signal at which linearity of the amplitude characteristic is still conserved (saturation power $P_{\rm sat}$). A typical value for TWQA is $P_{\rm sat}\approx 10^{-6}$ W for amplification of continuous signals (it proves to be correspondingly larger for amplification of pulsed signals).

In low-noise amplifiers of other types, saturation unavoidably involves restriction and nonlinear distortions of the spectra of the signals. In contrast, the theory of the nonlinear effects that arise when strong signals act on a QA shows and experiments confirm that in a QA even considerable saturation does not lead to appreciable distortions of this type.[4-6]

Of extreme importance in a number of practical applications of QA is high stability of the amplitude and phase characteristics of the amplifiers. Analysis has shown[5] that stability of these characteristics is primarily determined by the stability of the d.c. magnetic field required for operation of the QA.

Electromagnets and solenoids with superconductive coils have been specially developed in the USSR for QA in order to achieve high stability of the magnetic field (this was one of the first examples of practical application of the superconductivity effect outside the walls of physics laboratories). This made it possible to increase substantially the stability of quantum amplifiers and to reduce their dimensions. After the amplifier is turned on and a field of the needed strength has been obtained, the power supply of the magnet is turned off and the magnetic field is "frozen in."

In current TWQA the instability of the amplification coefficient amounts to 1–2%, while the phase instability is about a degree.[6,35] It has proved possible to decrease the phase instability to tenths and even hundredths of a degree by special measures (increasing the internal decoupling, preventing liquid helium from getting into the SWS, stabilizing the pump power and frequency, etc.[6,28]).

Two methods are used for cooling the high-frequency unit of a QA having a superconductive magnet to liquid-helium temperature. In the first one, the unit to be cooled is put into a metal Dewar container, or cryostat, into which one periodically pours (or syphons) liquid helium. As a rule, the evaporated helium is collected and liquified again in a separate cryogenic apparatus. In the second method special cryogenic machines are employed that are directly connected to the quantum amplifier and are a constituent part of it ("closed-cycle cryogenic machines").[6] Both cited refrigeration methods have their merits and defects, and the choice of the optimal system depends on the specific conditions of use.

Table II gives the parameters of some quantum amplifiers employed in long-range space communication systems and in radio astronomy. The table lists only the fundamental types of amplifiers from among those currently in use.

All the amplifiers cited in the table except the first one, which was built according to the above-described multiresonator scheme (see Fig. 2) are traveling-wave amplifiers. In the decimeter wavelength range, whenever one doesn't need to tune the frequency of the amplifier over a broad frequency range, an amplifier constructed according to the multiresonator design (first row of Table II) allows a larger passband than a TWQA for the same range (second row of Table II).

In spite of the greater efficiency of rutile over ruby in the range 1–7 GHz that theoretical estimates imply,[30] in practice quantum amplifiers based on rutile are in most cases still inferior to ruby amplifiers in this range in their fundamental amplifier parameters (see Table II).

Analogous estimates that indicate superiority of rutile have also been applied to the 8-mm range, which is of considerable interest for radioastronomy. However, attempts to develop a TWQA for this range based on rutile that have been undertaken in the USA[31] and in France[32] have not yet led to design of devices suitable for practical applications.[33] In these TWQA wave retardation was brought about by the high dielectric permittivity of rutile that filled the waveguide. Because of the insufficient retardation thus attained, these amplifiers did not yield the required amplification at 4.2 °K (the temperature of liquid helium at normal atmospheric pressure), and it was necessary to lower the temperature to 1.7 °K. This temperature decrease was attained by reducing the pressure in the cryostat by continuous pumping of the helium vapors with a vacuum pump. This considerably complicates the operation of the amplifiers.

A TWQA for the same range[25] developed in the USSR employs a highly efficient comb slow-wave system (see Fig. 3), while ruby was used as the active material. The required parameters were attained at 4.2 °K. These TWQA which are quantum amplifiers of highest frequency of those in operation[30] have been applied in radiotelescopes in the USSR since 1968 (for more details, see Sec. 4).

4. APPLICATION OF QUANTUM AMPLIFIERS

The growing demands on information capacity and long-range functioning of space communication lines with stations launched into outer space, together with the limited energy resources of these stations, have engendered a need of attaining as high as possible (at the current level of science and technology) an efficiency of the Earth-based radio receiving systems.

For this reason, quantum amplifiers have been widely used in the Earth-based outer-space communications systems in combination with large antennas specially adapted for operation with quantum amplifiers.

The noise temperature T_s of the entire radio receiving system (i.e., the aggregate of the antenna and the radio receiving apparatus) is determined by the relationship

$$T_s = T_A + T_0 \frac{1-\eta}{\eta} + \frac{T_{n,\mathrm{QA}}}{\eta}; \tag{4.1}$$

Here T_A is the noise temperature of the antenna proper, which is a measure of the noise received by the antenna from the surrounding space, and η is the efficiency of the feeder line that connects the primary irradiator of the antenna with the quantum amplifier; $T_0 \approx 300$ °K is the temperature of the feeder line; $T_{n,\mathrm{QA}}$ is the noise temperature of the quantum amplifier.

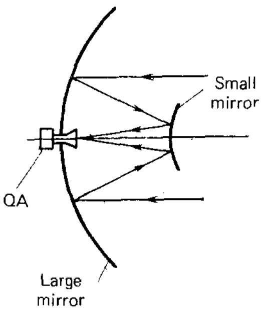

FIG. 4. Coupling of a QA with a Cassegrain-type antenna.

In order to realize the potentialities of the QA in reducing the noise temperature of the system, the first two terms in (4.1) must be small. This imposes certain requirements on the antenna design.

In particular, since the antenna feeder line contributes appreciably to the noise temperature (e.g., in the 3-cm range, a waveguide 1 m long makes contribution of about 10 °K), one must shorten to a minimum the length of the line between the QA and the irradiator of the antenna.

This has required development of special low-noise antennas.

Currently the most widespread type of low-noise antenna is the two-mirror antenna, which is called a Cassegrain antenna by analogy with the well-known optical system.

Figure 4 shows a diagram of the coupling of a quantum amplifier with such an antenna. Owing to the two-mirror design principle of the antenna, the quantum amplifier can be placed near the vertex of the large mirror of the primary irradiator. This allows one to reduce to a minimum the length of the wave guide line and it also provides easy access to the quantum amplifier and to the other receiving apparatus (when one employs an ordinary one-mirror parabolic antenna, one cannot simultaneously satisfy these two requirements).

In the described systems involving quantum amplifiers, one can realize a noise temperature T_s of the entire radio receiving system of about several tens of °K (the record values for systems with large antennas are as low as ~20 °K in the centimeter range with an antenna facing the zenith).

Figure 5 shows one of the low-noise antennas of an outer-space communication system that is equipped with quantum amplifiers. The quantum amplifiers have allowed reliable communication with automatic interplanetary stations (AIS) of the "Zond," "Luna," "Mars," and "Venera" series during the course of very important space experiments, including photography of the back side of the Moon and in obtaining the unique photographs of the surface of Venus in the flights of the "Venera-9" and "Venera-10" AIS.

In the American Earth-based outer-space communi-

FIG. 5. Antenna of a long-range space communication system equipped with quantum amplifiers.

cations systems (in American terminology, deep space networks), which were set up at a number of points on the Earth, quantum amplifiers have also been used as low-noise input receiving instruments. Thus, in the best-known Goldstone complex of NASA, which includes three antennas 26 m in diameter and one 64 m in diameter, 1–2 quantum amplifiers for the 12-cm wavelength range were installed in each antenna, while in the 64-m antenna several more amplifiers for other ranges were installed in addition.[35] The aforementioned amplifiers are regularly used to receive information from interplanetary stations (including the AIS of the "Pioneer," "Mariner," "Viking," etc., series) for radar observation of the planets and in various radioastronomical studies, including the Soviet-American experiments in radiointerferometry (see below for more details).

It is considerably more complicated to ensure the needed information capacity of the outer-space communication lines (Fig. 6) in flights of AIS to the outer planets of the solar system. Under these conditions, the importance of quantum amplifiers increases even more.

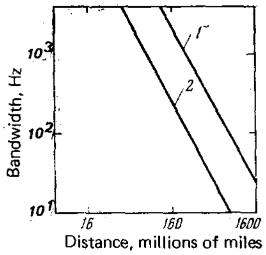

FIG. 6. Information capacity of the Cosmos-Earth communication line.[34] Noise temperature of the Earth-based system $T_s = 50°\mathrm{K}$; wavelength 13 cm; diameter of the spaceborne antenna mirror 1.2 m; diameter of the Earth-based antenna mirror 64 m. Power of spaceborne transmitter 10 W (1) and 1 W (2).

The application of quantum amplifiers in radioastronomy, which has increased the sensitivity of radiotelescopes by more than an order of magnitude, has opened up new potentialities for radioastronomical studies and has expanded our knowledge of the Universe.

Thus, a fundamental discovery of modern astrophysics—the discovery of the remnant background cosmic radiation that has a temperature about 3 °K—was made in 1965 using a radio receiving apparatus containing a quantum amplifier.[36] The apparatus, which was designed for receiving weak signals reflected from a passive Earth satellite in the 7-cm wavelength range, owing to its extremely low noise temperature and exact calibration could distinctly record the states "anomalous" excess in the noise temperature of the antenna over the noise temperature arising from the heat radiation of the atmosphere.

The advances in planetary radar observation, this new branch of radioastronomy, are to a considerable extent also associated with the advent of quantum amplifiers.

At present quantum amplifiers are generally employed in the planetary radar stations in the USSR and the USA as the input low-noise amplifiers.

Radar observation of the planets Mercury, Mars, and Jupiter[38] was first carried out in the USSR by using a quantum amplifier that was specially developed for this purpose[37] and which replaced the previously employed parametric amplifier, and new radar studies of higher information capacity were carried out on the planet Venus. We can illustrate the role of quantum amplifiers in these studies with the following examples. In radar study of the planet Mercury during closest approach of this planet to Earth, one must accumulate the signal for 10–15 days, even when using a quantum amplifier, in order to distinguish the signal from noise. Without using a QA, one would have to accumulate the signal during many cycles of approach of the planet, which repeat every three months. This would extend the observation to several years. Application of QA has made it possible to perform reliable radar observations of Venus and Mars over large regions of their trajectories, which is essential in flight correction of interplanetary stations.

One of the very important fields of radioastronomy is the study of the spectral lines of cosmic radio emission. These studies were initiated about 25 years ago when the first of the radiofrequency spectral lines of cosmic radiation arising from quantum transitions in the hyperfine structure of the spectrum of neutral hydrogen was found at the wavelength of 21 cm. Observations of the 21-cm line have become widely applied in studying the interstellar medium and they have provided astronomy with fundamental information on the structure and dynamics of the Galaxy. Application of quantum amplifiers[39-41] has increased by several orders of magnitude the volume of the region of the Universe accessible to study by this method.

It is of great interest to study the regions of excited and ionized hydrogen (the so-called H II regions), which are closely connected with stars and which are an important constituent of the Galaxy. The spectral lines of the radio emission of excited hydrogen (lines of the recombination spectrum) are about two orders of magnitude lower in intensity than the neutral hydrogen line at wavelength 21 cm. Therefore prior attempts by radioastronomers of a number of countries to detect these lines were unseccessful.

Here we must make some explanations. The sensitivity of a radiotelescope (the threshold signal expressed in °K of antenna temperature) is determined by the formula[42]

$$\Delta T = \alpha \frac{T_s}{\sqrt{\Delta f \cdot \tau}}; \tag{4.2}$$

Here T_s is the noise temperature of the entire radio receiving system [see (4.1)]; Δf is the passband of the radiometer up to the detector; τ is the time constant of the integrator following the detector; and α is a coefficient (of the order of unity) that depends on the type of radiometer and integrator.

When one carries out radioastronomical observations in the continuous spectrum, the sensitivity of the radiotelescope (which is usually limited by the available observation time for a given integration time τ) can be increased not only by diminishing the noise temperature T_s, but also by expanding the passband Δf of the radiometer. This method is widely applied in radioastronomical observations in the continuous spectrum. However, in studying spectral lines of cosmic radioemission, the passband must be considerably smaller than the width of the spectral line. Even in the millimeter wavelength range, the latter does not exceed several MHz, while in individual cases it is of the order of kHz. Therefore, in this type of radioastronomical studies, the only method of increasing sensitivity is to lower the noise temperature T_s of the system. In this regard the low-noise amplifiers of other types (traveling-wave electron tubes, parametric amplifiers, tunnel amplifiers, etc.), which are widely applied in continuous-spectrum radiometers where they allow a high radiometric sensitivity owing to their wide passband, are considerably inferior to quantum amplifiers in observations of spectral lines.

The detection by Soviet radioastronomers of spectral lines of the radioemission of excited hydrogen became possible after a marked (about twentyfold) increase in the sensitivity of spectral radiometers that was attained by using quantum amplifiers. The profile of the spectral line of excited galactic hydrogen (Fig. 7) has been observed for the first time by using a 5-cm-wavelength TWQA and systematic studies of this line have been conducted in a number of nebulae,[43,44] including extremely weak sources—down to an intensity of 0.06 °K.6)

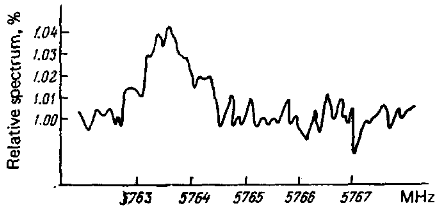

FIG. 7. Spectrogram of the radioemission line of excited hydrogen in the Omega nebula in the 5-cm range. Four spectrograms are averaged; the mean intensity outside the line is taken as unity.

The installation of 8-cm traveling-wave quantum amplifiers in the RT22 radiotelescopes of the Institute of Physics of the Academy of Sciences of the USSR (FIAN) and of the Crimean Astrophysical Observatory (CAO) has permitted reducing the overall noise temperature by a factor of about 25.[46] A sensitivity was attained of $\Delta T = 0.05$ °K ($\Delta f = 1$ MHz, $\tau = 50$ sec) is spectral observations, and $\Delta T = 0.08$ °K ($\Delta f = 20$ MHz, $\tau = 1$ sec) in observations in the continuous spectrum. We should note that the main contribution to the noise temperature comes from the input waveguide units of the radiometer,[46] so that the stated values can be improved (e.g., by cooling the input ferrite modulator, etc.), especially when using the amplifier in a radiointerferometer (see below). This is because the number of waveguide units at the input is diminished.

The attained high sensitivity has allowed detection of the first spectral line in the millimeter wavelength range; the radioemission line of excited hydrogen H56 α at 0.8 cm.[47] Studies of this line have made it possible to proceed from obtaining the integral characteristics to studying the distribution of physical conditions throughout the volume of the source, owing to the high angular resolution of the RT22 radiotelescope at the 0.8 cm wavelength.

The discovery and extensive study of the spectral radioemission lines of galactic hydrogen have made it possible to obtain a set of important scientific results. Thus, the existence has been proved of a discrete spectrum of excited hydrogen in the radio range, the absence of Stark broadening of the spectral lines has been established (the latter has forced a reconsideration of existing theory), the electron temperature and distribution of electron matter have been determined in different regions of the Galaxy, and the dynamics of its movement has been studied.[48]

In 1973–1974, the RT22 radiotelescopes were fitted with TWQA for the 1.25–1.35 cm range. This range is of especial interest for radioastronomy, since this is just where the spectral radioemission lines of water-vapor and ammonia molecules were detected in the late sixties in a number of regions of the Galaxy. Here, as a rule, the water-vapor lines was unusually narrow (of the order of tens of kHz). This is explained by the effect of stimulated emission in cosmic nonequilibrium systems (the "cosmic maser"). Further studies of this line can cast light on the process of star formation.

Application of quantum amplifiers has considerably increased the number of weakly emitting regions in which such phenomena can be studied.

In the 1.35-cm range, an overall noise temperature T_s of the system has been obtained in the CAO RT22

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6) A spectral radioemission line of excited helium has been detected in the same apparatus in the 5-cm wavelength range.[45]

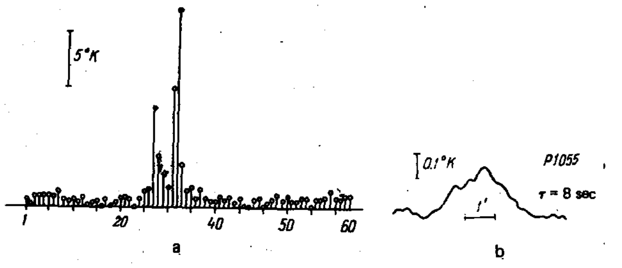

FIG. 8. Examples of recordings obtained by using a TWQA at the 1.35 cm wavelength. a) Spectrogram of the emission line of water vapor in the source *W*3 (readings every 115 kHz); b) recording of the radioemission of the source P 1055 in the continuous spectrum.

radiotelescope in the range from 80 to 120 °K (depending on the complexity of the input waveguide tract of the radiometer and on the state of the atmosphere). This corresponds to an approximately twentyfold gain in sensitivity.

Figure 8 shows examples of recordings[49] obtained by employing amplifiers in the 1.35-cm range in the FIAN RT22 (Fig. 8a) and CAO RT22 (Fig. 8b) radiotelescopes.

Until recently no radiometric apparatus had been built abroad that had the sensitivity in the 0.8–1.3 cm range that was attained in the RT22 radiotelescopes, which are equipped with quantum amplifiers.[30,35,65] This has been true not only of spectral radiometers, but also of the continuous-spectrum radiometers that are being employed in radiotelescopes.[50] The high sensitivity of the apparatus in these wavelength ranges has made it possible to use the RT22 radiotelescopes for a series of currently important radioastronomical studies also in the continuous spectrum: measuring the emission intensity at 0.8 and 1.35 cm from many cosmic sources (quasars, galaxies, supernova remnants, etc.) and tracing the flux variation over several years[51-53]; measuring and interrelating with high accuracy at the states wavelengths the brightness temperatures of almost all the planets of the Solar System,[54,55] etc.

Recently interest has grown in radioastronomical observations in the shorter millimeter wavelengths, especially in connection with the discovery in this range of cosmic emission lines corresponding to rotational transitions of a number of molecules. The sensitivity of radiometers at these wavelengths is very low. Hence the problem of building efficient low-noise input devices at wavelengths shorter than 0.8 cm is very urgent.

The efficiency of parametric amplifiers in these ranges is small, while the design of effective QA, especially TWQA, for radiotelescopes at short millimeter wavelengths involves great difficulties.

Taking these circumstances into account the following low-noise apparatus seems highly promising for application at short millimeter wavelengths. The described TWQA for the 1.35-cm (or 0.8-cm) range, can be used as an intermediate-frequency low-noise amplifier and as a tunable low-noise frequency converter (Josephson,[56] varactor, etc.) installed at the input of the slow-wave system of the TWQA and cooled along with it to liquid-helium temperature. One can hope that the overall noise temperature of this instrument will not on the hole exceed 100 °K almost throughout the whole millimeter wavelength range.

It has proved highly effective to apply quantum amplifiers in radiointerferometers with very long baselines, which recently have become a powerful means of studying quasars and galactic nuclei—extremely interesting cosmic objects whose nature is one of the fundamental problems of study in modern astrophysics. Indirect data appeared in the mid-sixties that most of these objects have extremely small angular dimensions—less than a thousandth of a second of angle. We clearly need the construction of radioastronomical instruments of angular resolution of the stated order to study them. This has served as a stimulus for building very-long-baseline radiointerferometers (VLBRI) that allow one to obtain the needed high resolution by separating the endpoints of the radiointerferometer to the maximum possible distance within the limits of the globe (8–10 thousand km) and by using the shortwave part of the centimeter wavelength range.[7]

The VLBRI method consists in independent synchronous detection of signals from the studied radio source at the ends of the baseline and subsequent joint correlation processing of these signals on a computer. The coherent conversion of the received high-frequency signals into videofrequency signals recorded on a magnetic tape and also the synchronization of the records at the different points are performed by using highly stable quantum (atomic) frequency standards.[42,57-60]

The first experiments on intercontinental baselines, which were conducted at 18 and 6 cm wavelengths, showed that one must employ the shorter centimeter wavelengths and a receiving apparatus with the maximum possible sensitivity for efficient operation of VLBRI.[58,60]

Just as in the studies of spectral lines, the possibilities of enhancing the sensitivity of the receiving apparatus by increasing the bandwidth of received signals are restricted here. In this case the restrictions arise from the means of detecting the signals; in the present-day apparatus the maximum frequency of recordable signals does not exceed several MHz.[61] Hence the only way to increase the sensitivity of VLBRI is to use receiving instruments having the minimum possible noise temperature. In this regard it has been concluded that the most suitable receiving instrument for VLBRI, especially for short centimeter wavelengths, is the traveling-wave quantum amplifier.[30,60]

Both of the stated conditions—use of short centimeter wavelengths and highly sensitive receiving instruments —have been fulfilled in joint Soviet-American observations of compact cosmic radioemission sources per-

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[7] The angular resolution of a radiointerferometer (in radians) is approximately equal to the ratio of the wavelength to the length of the baseline.

formed at the wavelength 3.5 cm in 1971 in an intercontinental radiointerferometer with a USSR–USA baseline about 10 thousand km long.[62-64]

The angular resolution realized in this radiointerferometer and the high sensitivity [a flux of less than one flux unit (10^{-26} W/m^2·Hz) was detected at a level tenfold higher than the noise sensitivity] that was made possible by using quantum amplifiers[63] enabled the observers to reveal the complex structure of a number of compact sources (quasars, galaxies, etc.) and to establish the existence of them of compact components whose angular dimensions are less than 3×10^{-4} seconds of angle.[64] It takes an even shorter wavelength to study these components. VLBRI experiments were performed in 1976 at the wavelength 1.35 cm with telescopes situated on three continents: in the USSR (Crimea, CAO RT22 radiotelescope), in the USA, and in Australia. The CAO RT22 radiotelescope where a quantum amplifier was used, has the lowest noise temperature.[29,65] In these experiments an angular resolution of about 10^{-4} seconds of angle was attained.[65]

The conversion of VLBRI into an instrument for systematic radioastronomical observations will allow us to extend considerably our knowledge of the Universe. The VLBRI method can also find a number of very important applications in geophysics and navigation. As a rule, one requires here the maximum possible sensitivity, which is made possible by quantum amplifiers.[66,67]

Thus, in the period that has elapsed since the time of discovery of the principle of quantum amplification, quantum amplifiers of radio waves have been converted from laboratory research instruments into technically refined instruments whose application in outer-space communication and in radioastronomy has allowed us to obtain a number of important results in studying outer space.

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