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MICROWAVE TELECOMMUNICATIONS SYSTEMS

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Advanced microwave communications systems in the millimeter band, including the ground-based and those carried aboard satellites and high-altitude unmanned flight vehicles, are discussed. Such microwave systems offer unique opportunities in quite a number of different tasks due to their rapid deployment capability, all-weather operation, high reliability, absence of cables, capability of providing a wide frequency band in the data transmission channel, and ability to connect directly into existing networks of satellite, relay, and cellular communications. The use of millimeter waves significantly enhances the channel capacity, the noise immunity and reliability of data transmission while decreasing the size, mass, and energy consumption of the communications system.

The prospects and capabilities of cable-free microwave communications have currently been widely discussed. Not by chance, the greatest attention is paid to millimeter-band (MMB) systems. Indeed, quite successful solutions to the telecommunications task are achieved, for instance, in the case of long-range communications at a wavelength λ of 8 mm at distances up to 20–25 km ($P_{\mathrm{rad}} \sim 100$ mW) and for short-range interference-free (covert) communications at a wavelength λ of 5 mm and absorption in the atmosphere (for protection against interference) at the oxygen spectral line; the most compact medium-range, superhigh-directivity communications systems are designed in the 3-mm band. The MMB offers absolutely unique opportunities for many applications, among which one could mention intercomputer communications with data transmission rates of up to 1 Gbit/s or higher, inter-ATX and interbank telecommunications systems with capacities no less than 10^4 telephone channels, area-protection systems, telephone and TV communications with satellite towns and small settlements, etc.

1. GROUND-BASED MMB COMMUNICATIONS SYSTEMS

Ground-based (tropospheric) MMB communications systems usually provide operating ranges of no more than 20–25 km (with an output power between 100 mW and 1 W at wavelengths of about 8 mm). Greater lengths of communication link are precluded by radiowave absorption by hydrometeors, even in the windows of relative atmospheric transparency [1]. Figure 1 shows the effect of the water vapor on atmospheric transparency at various MMB frequencies, and Fig. 2 depicts the levels of radio wave absorption by rains of various intensities (20–100 mm/h) as functions of the communication range at the frequency 38 GHz for a 30-cm antenna diameter; we see that absorption is low in this range (less than 1%). However, already in the 3-mm band the ranges of existing systems which provide a communication reliability of 0.98 or better do not exceed 3–5 km in a rain of tropical intensity. In any case, atmospheric attenuation seriously hinders the development of MMB communications devices, but their small size, high (nearly cable) directivity, the ether purity (absence of radio interference in this band), wide bandwidth of the transmission channel, and relatively low costs make MMB communications systems more preferable for short ranges than centimeter-wave systems [2].

Duplex systems are in very wide use. Figure 3 shows the block diagram of the transmitter/receiver terminal of a duplex system [3]. Its main feature is two separate microwave sources, the transmitted signal generator and the receiver heterodyne. One could, however, restrict oneself to a single generator in each terminal, if the frequencies of the forward and backward transmission channels are spaced by the intermediate

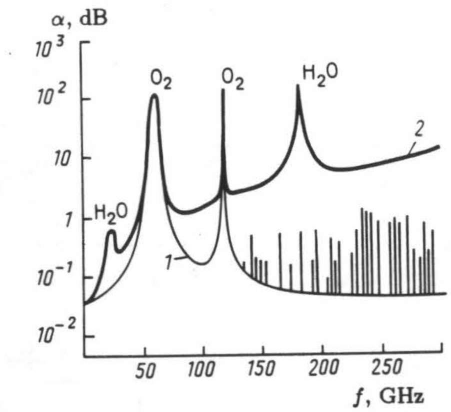

Fig. 1

Attenuation in the atmosphere (on a vertical path) in the absence (1) and presence (2) of water vapor (vapor density 2 g/cm^3).

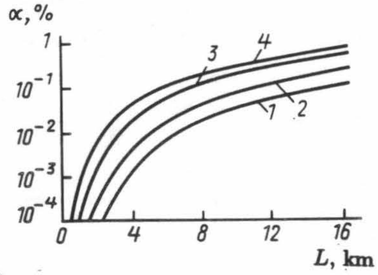

Fig. 2

Absorption α (in percent) of 8-mm radiation by rains with 20–100 mm/h intensities; a 150-mW, 38-GHz signal was measured on a ground path between antennas of 30-cm diameter; rain intensities are 20 mm/h (1), 30 mm/h (2), 60 mm/h (3), and 100 mm/h (4).

frequency; in that case, the mixing diode in the receive mode mixes the waves of the received signal and the unmodulated transmission (branched off at an attenuator-reduced power) of the internal oscillator which simultaneously serves as the heterodyne. Communications systems typically employ the phase (PM) or the frequency (FM) modulation. In the first case, the oscillator stability must be no worse than about 10^{-6}; in the second case the frequency stability requirements are less stringent (about 10^{-4}). In digital data transmission, as a rule, phase modulation in the PM mode is accomplished with pin-diodes, and frequency modulation in the FM mode is performed by varactors. Data transmission rates can be as high as 140 Mbit/s (the Siemens duplex system), but their typical values are 2 or 10 Mbit/s (all Russian systems developed at Istok and Era Research Institutes, at Bist Joint Venture, at Moscow University, etc., as well as foreign-developed systems by Alcatel, Nokia, Microwave Networks, etc.). Bearing in mind the limit value of the time constant of the existing pin-modulators (on the order of 10^{-11} s), one may assert that the data transmission rates can be increased at least to 10 Gbit/s. This would allow transportation of very large streams of digital data (e.g., aerospace data), transmitting wide-band signals to be processed in real time at the receiving terminal. Thus, the MMB systems emerge as a real competitor to the optical-fiber communications lines (OFCL) owing not only to their lower cost (OFCL require cables) but also to higher data transmission rates (the existing OFCL have maximum speeds on the order of 1 Gbit/s).

The most stable microwave communications are those based on PM. For transmission rates below 10 Mbit/s, PM can be performed both in the principal frequency channel (MMB) and at a lower frequency (100 to 1000 MHz), with a subsequent upward transformation. The latter option simplifies the master oscillator frequency stabilization circuit and provides an opportunity of using microstrip connections for the pin-modulators. The latter PM system is much more reliable and energy-saving, as shown by the research carried out at the Istok Institute [3]. The most short-wave duplex communications systems in the 3-mm

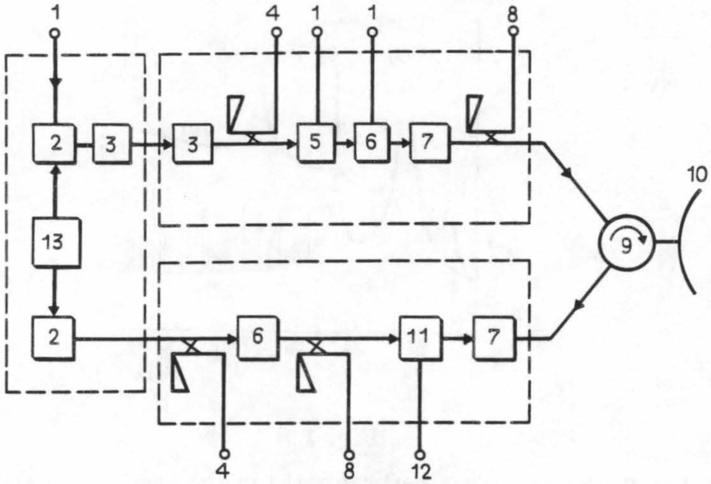

Fig. 3

Block diagram of transmitter/receiver terminal of a duplex 8-mm microwave communications system: (1) control signals, (2) avalanche- or Gunn-diode oscillators, (3) isolators, (4) signal outputs to automatic frequency control circuit, (5) phase modulator, (6) controlled attenuators, (7) waveguide band filters, (8) signal outputs to control circuit, (9) circulator, (10) antenna, (11) mixer/preamplifier, (12) IF output, (13) power source.

band (at 95 GHz) were developed by Istok, the most speedy systems by the foreign companies Siemens (140 Mbit/s) and Microwave Networks (45 Mbit/s).

Recently, in connection with the development of local computer networks which encompass individual buildings, the need for cable-free connection of computer terminals arose. For this purpose, Motorola Corp. (USA) developed its Altair microwave duplex communications system operating at 18 GHz with a data transmission rate of 470 Kbit/s [4]. This is the first experience in microwave connection of computers into local area networks with data packet transmission in Ethernet format. This experience proved rather successful (the company began serial production of Altair systems), despite the moderate throughput of the communications channel (comparable, it is true, with the rate of data exchange between an AT computer processor and the hard disk in its storage system). The Altair system consists of a control unit and several (up to five) user modules, to which up to six computers may be connected. The control unit acts as an intelligent bridge which reads a packet's address and directs the packet to the appropriate user module. The modules are connected to computers in a very simple manner and provide communication distances of up to 50 m (or about 10 m if obstacles such as dry-laid walls are present). Future systems of this type will have greater throughputs and a much wider scope of applications.

2. SATELLITE COMMUNICATIONS SYSTEMS

In the last 20 years, centimeter-band microwave communications satellites became an integral part of the world telecommunications system [5, 6]. However, the need to broaden the frequency band (to increase the link capacity) and to reduce the sizes of onboard terminals dictates transition to shorter, i. e., millimeter, waves. Operation in the MMB makes it possible to increase the volume of transmitted data and their transmission rate, to reduce the number of geostationary satellites, and to provide, without having to connect to local cellular networks, individual communications via satellite with cars, aircraft, sea ships, hotels, in-field sites, etc. High electrodynamic gains and small apertures of MMB antennas, high noise immunity and directivity of transmission are also important advantages of the MMB. The latter, in particular, enables one to reduce the onboard transmitter power and increase the channel reliability.

MMB is usually associated with high attenuation of radio waves in the gases which constitute the atmosphere (see Fig. 1) and in hydrometeors. This is true for horizontal tropospheric paths, but for vertical or slanted space paths the equivalent thickness of the atmosphere does not exceed 1.5 km, which corresponds to all-weather transparency virtually over the entire MMB.

Small countries could particularly benefit from using MMB communications satellites, because the surface area irradiated from the satellite becomes much smaller, fitting within the country's boundaries. So it is not surprising that the pioneers in developing MMB communications satellites are Japan [7–10], Italy [11], and Germany [12, 13], while the largest space powers Russia, USA, and China [15, 16] are only starting working in this area.

The Japanese Sakura satellites (CS-2A, -2B, -3A, -B) [7], the Italian Italsat [11], the German DFS-Kopernikus [12], the European Community's Olympus-1 [13] are currently operating in the MMB. The experimental MMB-oriented satellite programs ACTS [14, 15] and Nortsar (USA), ETS-6 (Japan) [7–9] are under way.

Satellite communications are implemented by the duplex scheme with far spaced frequencies of the forward and backward transmission channels. As yet, relatively low frequencies (20/30 GHz) are employed, but experiments are also performed at 40/60 GHz and research is planned on designing personal and moving-vehicle communications trunks in the 40/50 GHz band (the numerator is the satellite-to-Earth channel frequency, the denominator is the Earth-to-satellite frequency).

The Italsat program is typical of the current state of MMB research. It is aimed at creating an operational digital satellite network in combination with a ground-based microwave network. The Italian program incorporates quite a number of innovations: use of the 20/30 GHz band, coverage of the country' territory by several narrow beams which are switched on board the satellite. Providing communications in the interests of Italian state offices and private companies, the Italsat satellite, launched in 1991, handles telephone communications systems, high-speed transmission of digital data, teleconferencing, and experiments in the promising 40/50 GHz band. The geostationary satellite has three 20/30 GHz repeaters with a 10 W output power and a 12 Mbit/s information transmission rate; six high-speed (147 Mbit/s) repeaters of the 20/30 GHz band with a 20 W power; a 40/50 GHz radio beacon; two antennas 1.95 m in diameter with six 0.5° beams, covering areas of about 300 km in diameter each at the Earth surface. The ground antennas are 1.5 and 3.5 m in diameter, with gains of 48 to 63 dB, ensuring a high reception quality with an error probability of no more than about 10^{-6} over 99% of the year, with receiver noise temperatures of 200 to 500 K.

The two DFS-Kopernikus satellites developed by Siemens [12] (launched in 1989 and 1990) provide two-way TV, radio-telephone, fax, and high-speed (140 Mbit/s) digital communication at the frequencies of 20/30 GHz between 30 Earth stations (with antenna diameters of 3.5 to 11 m) at the territory of Germany and other European countries. The Earth stations are equipped with 20-GHz receivers cooled to helium temperatures, with a noise temperature of about 100 K, and 30-GHz, 1-kW TWT transmitters.

The European Space Agency (ESA), with the participation of 60 companies from Italy, Belgium, Great Britain, etc., has launched in 1989 the most powerful multipurpose experimental communications satellite Olympia with a total mass of 3,300 kg and a 600-kg payload, intended to be operational for 10 years [13]. In addition to supporting research in telecommunication systems operating in the promising bands of 12/20, 20/30, 40/50, and 50/60 GHz, a wide scientific programme is envisaged for studying the effects of hydrometeors and developing techniques for the suppression of deep signal fading due to changing weather conditions and phase and/or polarization distortions.

The first experimental MMB communications satellite was launched in Japan in 1977. It operated at 20/30 GHz. Japan's island location and mountainous terrain make satellite communications highly efficient, especially due to the existence of a large network of radio relay lines at 4, 6, and 11 GHz. However, a high density of ether occupation by centimeter transmissions also favors transition to the MMB in satellite communications. In the 1980s, several Japanese geostationary satellites of the ETS (Experimental Technological Satellite) series were launched successfully. The most advanced of them, the ETS-6 (launched in 1994), carries a compact (11 kg) 40/50 GHz repeater for experiments on personal communications using Earth terminals with 30-cm antennas and a satellite terminal with a 40-cm antenna, with 0.5-W transmitter output powers. The receivers have a 2-GHz intermediate frequency, a noise factor of 6 dB, and heterodynes with very stable frequency (about 10^{-7}). Furthermore, in 1994-95 Japan plans to orbit the largest satellite CS-1 with 70 repeaters and a multibeam (10–20 beams) onboard antenna, providing 100 000 duplex communication channels.

A very interesting project by NASA (ATCS) and Norstar in the USA (the total cost of the demonstration version alone is $500 million) reached its implementation stage after 1991 [7, 14, 15]. In the 20/30 GHz band, the most advanced system of antenna equipment is to be developed, with a switching array, a system for instant beam retargeting, and a signal processor. There will be a total of 1728 channels with a data transmission rate of up to 110 Mbit/s. The satellite is equipped with three separate antennas, two of which, 2.2 and 3.3 m in diameter, serve respectively for signal reception and transmission in the working channels. The third antenna, 1 m in diameter, uses an auxiliary channel for controlling the beam attitudes of the working antennas. The repeater contains a receiver with a low-noise amplifier with HEMT transistors, a 46-W TWT transmitter, and circuitry for automatic compensation of signal fading due to rain.

3. REGIONAL MICROWAVE SYSTEMS BASED ON UNMANNED AIRCRAFT

In Russia, as well as in some other European countries (Czechia, Hungary, Italy, Greece), research is also carried out on nonsatellite projects of communications systems based on high-altitude (15–25 km) unmanned aircraft of a regional scope. The essence of these proposals is to use such aircraft as high-altitude platforms which relay the radio signals of a multichannel communications system in the centimeter and decimeter bands, as well as the signals of high-directivity, high-speed intercomputer communication lines in the millimeter band. The aircraft could be a high-altitude airplane or helicopter controlled by an autopilot or a ground radio link, a balloon, or an airship. However, the best option appears to be a light airplane with a wing span of 12–15 m and a mass of 100–150 kg, for which there are practically no safety problems in case of controllability loss, because parachute devices can be used to salvage it in emergency. The aircraft could carry various telemetry equipment, as well as communications systems operating in the optical, infrared, and microwave bands. Because of very high maintenance costs of both satellite and manned airplane or helicopter carriers, the use of unmanned vehicles is important in implementing the following projects.

1. Assessment of the states of the Earth surface, the ocean, and the atmosphere in the visible, IR, and microwave bands by both active (millimeter and centimeter radars, ground-based tracing lidars in conjunction with corner reflectors aboard high-altitude unmanned aircraft) and passive means (optical and IR-array receivers of reflected solar radiation, IR and microwave radiometers) in the interests of geophysics, ecology, and military technology.
2. Directed wide-band (1–2 GHz) point-to-point radio communications in the MMB at 30–150 GHz via a small-size (5–10 kg) onboard repeater that provides real-time data transmission rates up to 150 Mbit/s, including intercomputer lines, telephone communications across 10^5 channels, TV broadcasting over 50–100 channels, intercellular communications with the high-altitude unmanned aircraft serving as cell nuclei, etc.
3. Omnidirectional intracellular radio communications in the centimeter band with a territory coverage of up to 10^5 km^2, including an aircraft-relayed nucleus of a safety system, for receiving alarm signals from any point of the controlled territory and transmitting them directedly in the millimeter band to the control center. A regional bearing and navigation system could be organized, either off-line or connected to a global satellite navigation system.
4. Intracellular personal telephone connection in the centimeter and decimeter bands.
5. Intercellular highly directed wide-band radio communications between the cell-nucleus unmanned aircraft in the MMB, including over-troposphere interference-free communications with a 60-GHz carrier.

Communications via unmanned aircraft-based repeaters have numerous advantages. For instance, they greatly increase the range of wide-band MMB communication, because the signal path runs mainly outside (i.e., above) the troposphere, which has, as mentioned above, an equivalent vertical thickness of no more than 1.5 km: with an airborne repeater, the communication range limit could be increased to 100–150 km as compared with 20 km for a horizontal ground path. Moreover, the MMB relay lines with airborne repeaters allow the relay base (the distance between the repeaters) to be increased to 900 km. The onboard MMB repeater based on integral modules could be no heavier than 5 kg, with an antenna diameter no larger than 30 cm, an energy consumption of 200 W or less, a radiated microwave power of 0.1–1 W, and a sensitivity of the duplex repeater receivers of 0.2 K s.

If phased MMB antenna arrays are employed on board an unmanned vehicle (the total mass of the onboard radio system then increases to 10–15 kg), electronic scanning of the underlying surface could be performed across an area of up to 100 km^2 at a Rayleigh resolution of 30–100 m. Applying superresolution algorithms based on mathematical reduction methods [17, 18], one could provide a resolution of 1–5 m not only in the active (synthetic-aperture radars) observation mode, but also in the passive (radiometric) mode.

Moreover, modern morphological methods for the analysis of optical, IR, and microwave images can provide efficient recognition of low-contrast objects by templates stored in the onboard computer [19].

The airborne systems are two or three orders of magnitude cheaper than the satellite ones, mobile, self-contained, and simple in maintenance. What is particularly important, they do not require such a high level of long-term reliability as the costly satellite modules do. Spending no more than 3–7 days at the working point and operating in the shuttle mode, the airborne modules could undergo weekly prophilactic tests with unit replacement as necessary, proving to be much more reliable in the final account than the satellite systems.

The first stage of an airborne-relay project could envisage the creation of a regional communications system over a territory of $(1\text{–}10)\times 10^3$ km^2. With three high-altitude unmanned shuttles, two modes of operation could be realized: (1) an omnidirectional acquisition in the centimeter band of ground data on board the aircraft and an addressed transmission in the MMB to a ground-based receiving facility; (2) a highly-directed interference-immune super-wideband point-to-point transmission line 50–100 km long.

In conclusion we note that the prospects for microwave telecommunications systems are associated primarily with raising the channel capacities to 1–10 Gbit/s or more. This is possible only in the MMB. However, in passing to higher data transmission rates there arises a number of fundamental physical problems that are not completely solved. The most important of them are: (1) modulation to provide the radiation of supershort (few-period) PM and FM pulses; (2) oscillator frequency stabilization to about 10^{-7}–10^{-8}, which is especially important for phase modulation of signals; (3) demodulation with high-reliability signal recognition; (4) high-sensitivity reception of supershort radio pulses in direct amplification mode; etc.

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