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L. D. Bakhrah and A. A. Bliskavitskiĭ. *Optical-microwave beam formation methods for superwideband antennas.* At the present time narrowband close harmonic oscillations are mainly employed at radio frequencies. But this has not always been the case. Spark discharges, which give a superwideband (SWB) signal, was used by Hertz[1] and for 20 years thereafter to obtain electromagnetic waves. If the maximum and minimum frequencies of the signal spectrum are $f_{\max}$ and $f_{\min}$, then the relative bandwidth of the signal is $\eta = (f_{\max} - f_{\min})/f_{\max} + f_{\min})$. For transmitted signals usually $\eta \approx 1$, but in order to reduce η and simplify the equipment such signals are transferred, when possible, to a carrying frequency $f_0 \gg f_{\max}$. When such a transfer is made, however, in many cases the wave is strongly damped in the propagation medium or the noise temperature is high, which makes this method undesirable, i.e., signals without a carrying frequency but with $\eta \approx 1$ must be employed. Such signals are employed in over-the-horizon radar, microwave imaging of the deep interior of the earth, exploration of ice, radio communication with submarines, and so on.[2] No less important are applications of SWB signals with a carrier and $\eta > 0.33$. In particular, a radar transmitting powerful nano- and subnanosecond pulses, whose spectrum extends from low frequencies up to several gigahertz, makes it possible to detect and identify objects with a small effective scattering cross section.[3]

Although the advantages of SWB signals have been known for a long time, the use of such signals in radio systems is still very limited because it is difficult to switch high powers rapidly, narrowband microwave devices are inapplicable, and rectification of SWB signals is inadmissible. Thus nontraditional methods are required for formation, reception, and processing of SWB signals, and among such methods the optical-microwave methods stand out.[4,6] Optical-microwave devices include SWB fiberoptic distribution systems (FODS) and fiberoptic delay lines (FODL) for radio signals, optoelectronic microwave switches (OES), mixers, attenuators, etc. Single-mode fiberoptic waveguides have a number of advantages for transmission of a microwave signal on an optical carrier: extremely large bandwidths (hundreds of gigahertz per 1 km); ultralow per unit length losses (less than 0.5 dB/km), which are independent of the frequency of the modulating microwave signal; noise resistance; small transverse dimensions and mass; and, high flexibility. In constructing feeder systems for SWB band antennas, besides SWB transmission lines, frequency-independent power dividing and adding devices, attenuators, and phase shifters may be required. Fiber-optic and integral-optic devices have the advantage that their characteristics are independent of the frequency of the modulating radio signal.

A single-mode FODS usually employs a laser-diode transmitter operating in a state with a single highly stable longitudinal mode with microwave modulation. In this respect C^3, ROS, and RBO lasers are most promising.[4] The modulation bandwidth (BW) of the laser diode is bounded on one end by the frequency f_r of relaxation oscillations and at the other end by the effect of the parasitic elements of its equivalent electrical circuit. Since $f_r = (1/2\pi)(Ap/\tau_r)^{1/2}$, where A is the differential optical gain and p and τ_r are the density and lifetime of photons in the laser cavity, the modulation bandwidth can be increased by increasing A and p and decreasing τ_r and the parasitic reactivities.[4] It is expected that the modulation bandwidth of semiconductor superlattice lasers, which have high values of A and p, will be 60–100 GHz. Even today, however, a bandwidth of several tens of gigahertz is achievable using electrooptic traveling-wave modulators with synchronous electrode structure.[4] In order to obtain superwide bands heterostructure p-i-n photodiodes or photodiodes with a Schottky barrier, having bandwidths of up to 100 GHz and larger, are preferable.

A fiberoptic distribution system for radio signals differs significantly from traditional radio-frequency distribution systems. If the transfer power coefficient of a microwave distribution system of the form $1{:}N$ is inversely proportional to the number N of output channels, then in the case of the FODS with direct photodetection it is inversely proportional to N^2 (Ref. 5). In such an FODS the signal amplitude at the photodetector output is proportional to the squared amplitude of the input optical signal, so that an input signal with a dynamical range of $D^{1/2}$ can be detected only with a photodetector having dynamic range D, and this limits the dynamic range of the system. These drawbacks can be overcome only with the help of laser heterodyning. For the fiberoptic channel of the radio signal the following parameters are especially important: bandwidth, noise factor, dynamic range, nonlinear distortions, transfer power ratio, and amplitude and phase stability.

In a single-mode FODL the product of the delay time by the bandwidth is 10^6, which is two to three orders of magnitude higher than in other delay lines.[6] Such FODL can be used in the superwideband fiber-optic beamforming network of a multiple beam antenna array[7] shown in Fig. 1. Fiberoptic delay lines of appropriate length between each beam junction of the beamforming network and each element of the array are employed to form the beams of the directional pattern in the required directions. The lengths of the FODL are chosen so as to compensate the delay in excitation of the radiators of each plane wave arriving from the required direction. In order to form a beam in a direction making an angle ϑ with the normal to the array aperture the lengths of the neighboring FODL must differ by the amount $l = d \sin \vartheta / n$, where d is the array spacing and n is the group index of refraction of the lightguide. The superwide band of such an array results from the additional phase increase that arises, as the frequency changes, along the array due to the fact that the lengths of the FODL are different, being com-

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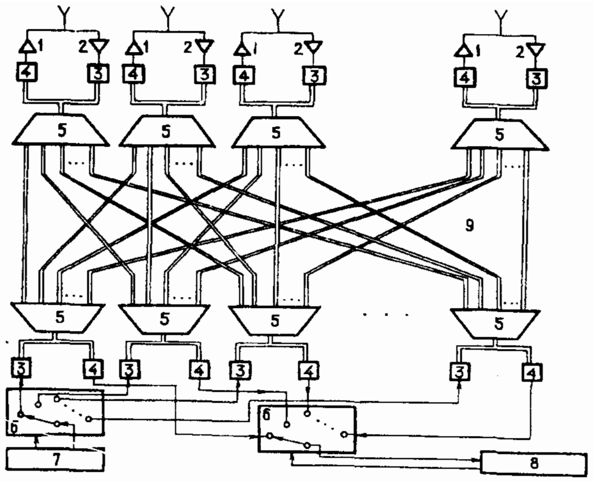

FIG. 1. Superwideband multiple beam active antenna array with a fiber-optic beamforming network. *1*—Microwave power amplifier, *2*—low-noise microwave amplifier, *3*—optical transmitter with microwave modulation, *4*—microwave photodetector, *5*—optical divider, summer, *6*—microwave switch, *7*—beamforming and transmission control units, *8*—signal processing and reception control unit, *9*—fiber-optic beamforming network based on fiber-optic delay lines.

pensated by the change in the relative spacing of the array (expressed in wavelengths), as a result of which the slope of the phase distribution and, correspondingly, the angular position of the beam remain unchanged. In this case the bandwidth of the array is limited by the bandwidth of the radiators as well as by the frequency at which the principal sidelobes of the directional pattern fall into the range of sight.

The previously unsolved problem of switching high power rapidly with highly precise timing can be solved with the help of a microwave OES, in which sharp optically controlled changes in the signal amplitude are made by means of the photoconductivity effect. These systems have superwide bands and are triggered with picosecond accuracy. The report gives information about three-dimensional microwave OES containing a GaAs crystal, which, when irradiated by the laser diode, is transferred within several picoseconds in an avalanche fashion into the conducting state throughout its entire volume and is then capable of transmitting gigawatt powers. A dc current is converted into a microwave signal hundreds of times more efficiently than with OES in the linear-photoconductivity mode.

Microwave OES can also be used in a frozen-wave oscillator or injected-wave oscillator[8] for generating short microwave bursts. The frozen-wave oscillator consists of several sections of a microwave transmission line, which are connected serially through microwave OES. The electric lengths of the sections are equal to one-half the microwave wavelength at which the generator should operate. When the OES are open the neighboring sections are charged up with the opposite charges and a frozen voltage distribution is formed along them. When the OES are closed synchronously this frozen wave starts to move both in the direction of the

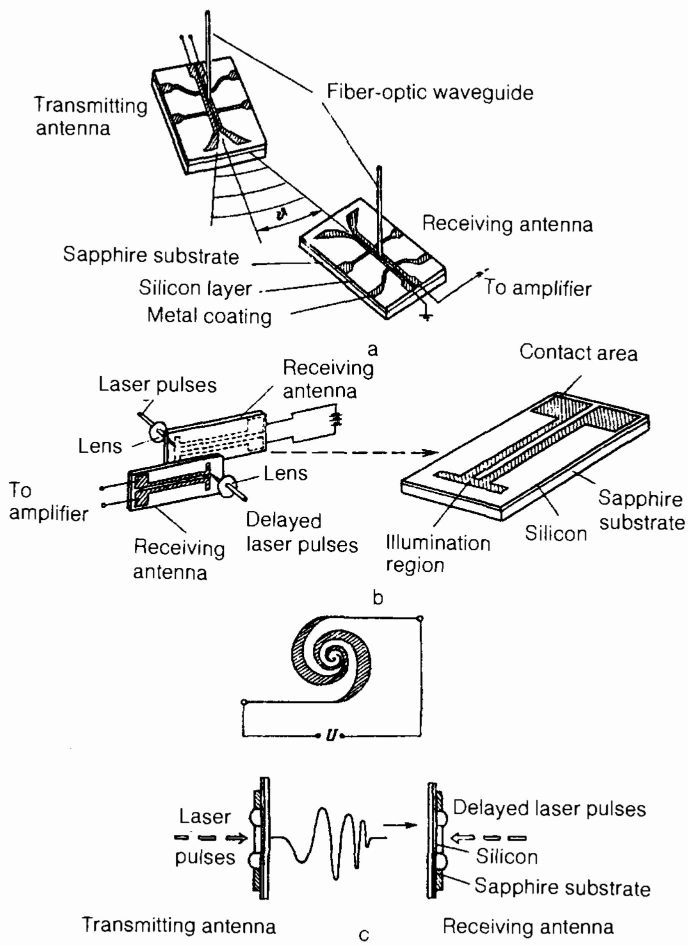

FIG. 2. Experiments with superwideband microstrip radiators, integrated with a microwave OES. a—With a radiator based on an exponential line. b—With a Hertz dipole. c—With a radiator based on flat self-complimenting double spiral.

load, where it is extracted in the form of microwave pulses, and in the direction of the open end of the transmission line, from which it is reflected and also moves toward the load. Thus N microwave periods can be generated by using in this generator N sections of a microwave transmission line.

Since microwave OES can operate synchronously, it is possible to build an active antenna array based on such microwave generators and, by adding the microwave power in free space, to overcome any limitations on peak power. By sending appropriately delayed controlling laser pulses to the OES in the array it is possible to phase the array, i.e., to form the required directional pattern of the antenna array. In order to guarantee that the bandwidth of such an array is superwide, superwideband radiators, integrated directly with an optical-microwave device, are required.[8] Figure 2 shows the following superwideband microstrip radiators integrated with an OES: radiators based on an exponential line, radiators based on flat self-complimentary double spirals with a constant angle of winding, and a Hertz dipole. All were fabricated by means of photolithography on a silicon-on-sapphire substrate. In order to investigate a radiator, voltage was applied to its electrodes, and as a result of excitation of the substrate with laser pulses short electromagnetic pulses were generated and emitted into space. The electromagnetic pulses induced on the electrodes a voltage identical to that on the receiving antenna, from which appropriately delayed laser pulses performed optoelectronic gating. The 2.5 mm in diameter spiral radiator had a bandwidth of 10–100 GHz, the 3.7 mm long exponential radiator with a 2.6 mm aperture had a bandwidth of about 120 GHz, and the band of the Hertz dipole with 50 mm long oscillators extended from 100 GHz to 2 THz,[7] making it possible to form a subpicosecond electromagnetic pulse and to study experimentally the propagation of the electromagnetic projectile[8,9] which is emitted by an array of such dipoles and whose energy decreases much more slowly than as the inverse square of the distance from the antenna, over tens of kilometers.

Optical-microwave beamforming methods for superwideband antennas, based on the latest achievements of optoelectronics, laser technology, and microwave technology, make it possible to achieve record-high bandwidths and antenna-feeder systems with excellent mass-to-size ratio, to simplify substantially the phasing of superwideband antenna arrays, to solve many aspects of the problem of electromagnetic compatibility, and to achieve picosecond timing accuracy in beamforming.

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