ISSN 1063-7850, Technical Physics Letters, 2011, Vol. 37, No. 2, pp. 178–181. © Pleiades Publishing, Ltd., 2011.
Original Russian Text © A. Mainwaring, A.L. Umnov, M.O. Shuralev, A.U. Eltsov, 2011, published in Pis'ma v Zhurnal Tekhnicheskoĭ Fiziki, 2011, Vol. 37, No. 4, pp. 68–75.

Steerable Reflect-Array Antenna Formed by Loaded Electric Dipoles

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Received September 27, 2010

Abstract—A reflect-array antenna with simple design, low cost, and electronically controlled directivity pattern for centimeter wavelength range is proposed. The antenna is based on a mirror formed by loaded electric dipoles.

DOI: 10.1134/S106378501102026X

The use of high-gain antenna systems with electrically controlled transmission/receipt directivity has good prospects in modern wireless communication systems, since these antennas make it possible to achieve desired signal quality even under conditions where the mutual arrangement of the radiator and receiver varies with the time. However, despite these advantages, antennas with steerable directivity patterns are still not widely used in wireless communication systems accessible on the big market of telecommunication equipment (for WiFi, WiMax, and 3G networks, etc.). There were only a few attempts at creating such antenna systems on a commercial level [1], but even these mostly implied the use of antennas with steerable directivity patterns on the side of base stations. To the best of the authors' knowledge, no cases of employing these antennas on the side of network users were reported.

The main reason for this situation is a significant cost of these devices, which is related to the expensiveness of microwave elements (phase shifters, waveguides, etc.) that constitute the basis of most phased antenna arrays—modern antenna systems with steerable directivity patterns.

The tasks of minimizing the number of expensive microwave elements, decreasing waveguide losses, and significantly reducing the cost of an antenna system while retaining all advantages of the antennas with electrically controlled directivity patterns can be solved within the framework of the concept of antenna arrays with spatial exciting of elements—passive scatterers with adjustable parameters [2]. Controlled variation of the parameters of scatterers can be achieved, e.g., by changing the parameters of load (lumped elements) involved in their design. This variation of the parameters of scatterers allows the phase and amplitude of re-radiated fields to be changed so as to form the desired directivity pattern of the entire system. Depending on the method of forming the directivity pattern, whereby either reflection of a primary wave from or its transmission through the array is used, these antennas are classified as reflect arrays [3, 4], lens arrays [5], or their combinations [6].

Characteristic features of the antennas under consideration are the presence of a strong electrodynamic coupling between elements and the complicated relationship between the parameters of scatterers and characteristics (amplitude and phase) of the re-radiated field. These features complicate the analysis of antennas and require creating special control systems.

The first antennas of this kind were proposed more than three decades ago [6], but they were not widely used for the aforementioned reasons. Recent development of microelectronics, computational facilities, and wide spreading of wireless communication systems led to a revival of the interest in antenna systems with steerable scatterers [2].

The present Letter describes the design of a reflect-array antenna based on a system of steerable scatterers, which ensures high gain and controllable directivity pattern.

Figure 1a shows a conceptual scheme of the proposed antenna [7, 8]. The system comprises a mirror (*1*), which is formed by 500 steerable scatterers, and an excited (*2*). The steerable scatterers are represented by electric dipoles loaded in the middle with a semiconductor diode (varicap) whose capacitance can be changed by varying the bias voltage. Variation of the load impedance allows the phase of the wave scattered by the dipole to be tuned; simultaneously, the amplitude of the scattered wave field is also varied.

The principle of operation of the proposed antenna can be illustrated by an analysis of its functioning in the regime of receipt of the radiation from an external

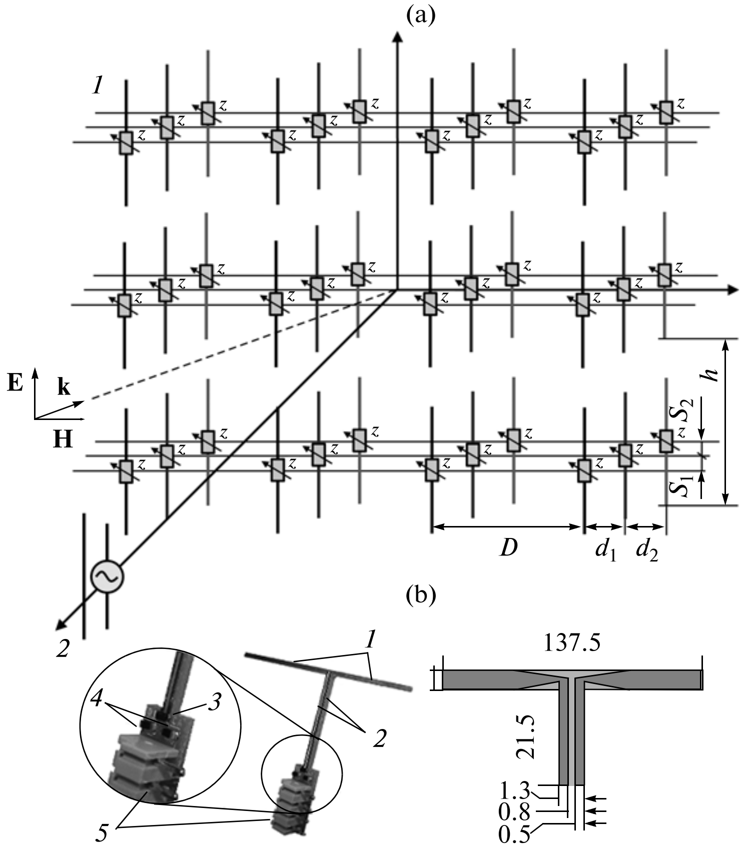

Fig. 1. Steerable reflect-array antenna: (a) conceptual diagram; (b) design and geometry (dimensions are indicated in millimeters). See text for explanations.

source. For the effective receipt, the loads of scatterers should be adjusted so that the phases of secondary waves created by the scatterer would provide the optimum addition of these waves at the site where the exciter is situated. The necessary values of load impedances depend on the direction of arrival of the wave incident upon the mirror. The possibility of changing these impedances must ensure the effective receipt of radiation from various directions.

Unfortunately, variation of the load impedance is accompanied by simultaneous changes in both phase and amplitude of the current, which does not allow the scatterer to be used for creating secondary radiation with arbitrary phase. In order to make possible phase tuning in the entire range, it is necessary to combine several layers of scatterers (Fig. 1a shows three-layer structure). The propagation of exciting and scattered waves between layers ensures the necessary constant phase shift, which is added to the phase shift provided by variation of the load impedance. Scatterers that form the mirror are not independent since there is a strong electrodynamic coupling between these elements. Therefore, the scattering properties of each element of the mirror are not only determined by the load of this particular element, but also depend on the loads of surrounding scatterers.

Figure 1b shows the design and geometry of a scatterer used in the experimental prototype (dimensions are indicated in millimeters). The scatterer implemented on a single-sided printed board comprises dipole arms (*1*), slot-line of impedance transformer (*2*), varicap (*3*) that is connected to the slotline, inductors (*4*), which separate the RF part of the scatterer from control lines (*5*) supplying bias voltage to the varicap via the contact unit connecting control lines to the scatterer. The long transmission line (impedance transformer) is introduced into the system for expanding the range of variation of the load impedance at the dipole input. The distances between scatterers in the mirror (Fig. 1a) are as follows: $D = 3$ cm; $d_1 = d_2 = 1$ cm; $s_1 = s_2 = 27$ mm; and $h = 15$ cm.

The geometric parameters of the scatterer and distances between scatterers in the mirror were selected based on the results of numerical modeling that carried out using HFSS program package. In calculations, it was assumed that the scatterer material parameters corresponded to those of FR4 fiberglass reinforced epoxy laminate, with the dielectric substrate and metal layer thicknesses of 1.5 and 0.05 mm, respectively, a dielectric permittivity of 4.9, and a loss tangent of 0.03.

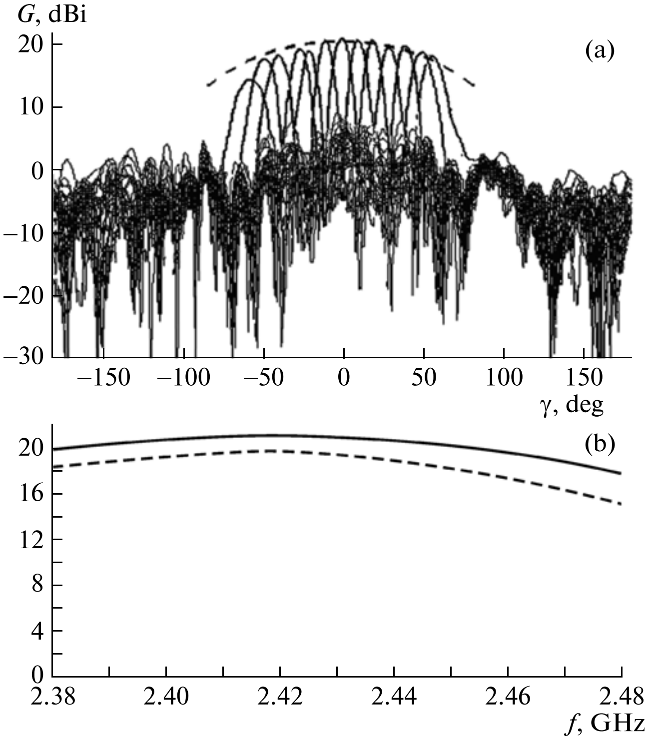

Fig. 2. (a) Antenna directivity patterns in the azimuthal plane; (b) plots of the antenna gain versus frequency.

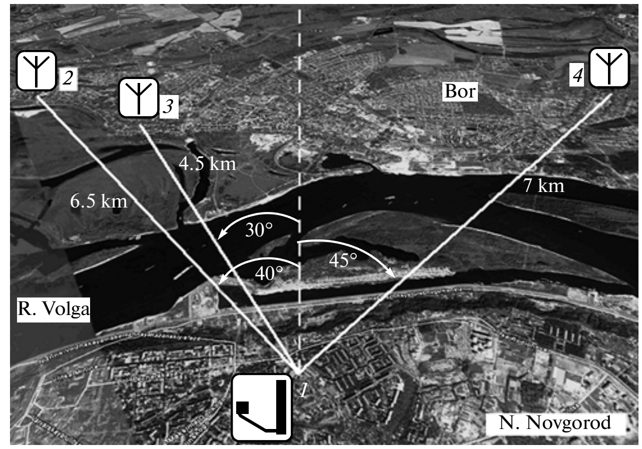

Fig. 3. Scheme of channels for wireless communications across a river.

The role of a controlled load of the scatterer was played by a varicap (MA4ST1240 ODS1279). According to the manufacturer's specification, variation of the bias voltage within 0–12 V leads to a change in the device capacitance from 13 to 1.12 pF, while the active resistance slightly varies within 1.2–1.1 Ω. The control line was connected to the scatterer via ILC-0603 (68 nH) inductors.

The experiments for determining parameters of the proposed antenna were performed in an echo-free antenna chamber. The antenna tuning (setting bias voltages on all diodes in the scatterers for all angles of wave arrival) was carried out in an automated regime using algorithms of multidimensional optimization with respect to the maximum of received signal.

Figure 2a shows the directivity patterns obtained in the course of these experiments for the antenna tuned in various azimuthal directions. Solid curves represent the experimental data, while dashed curve shows theoretical (cosine-shaped) decay of the gain that is related to a decrease in the effective area of antenna cross section. In the 2.4 GHz frequency range, the maximum gain was 21.5 dBi, and the main lobe of the directivity pattern was scanned in the horizontal and vertical planes within ±60°/±15° for the overall antenna dimensions of 100 × 60 × 30 cm.

Figure 2b illustrates broadband characteristics of the proposed antenna. Solid curve shows the gain *G* of the antenna tuned at 2.415 GHz in the direction of tilt angle 0° and azimuth 0°. The bandwidth on a level of −1 dB is to 47 MHz, which corresponds to four frequency channels of the WiFi system. Dashed curve shows the gain *G* of the antenna tuned at 2.415 GHz in the direction of tilt angle 0° and azimuth 30°. Here, the bandwidth on a level of −1 dB is 45 MHz, which also corresponds to four frequency channels of the WiFi system. A maximum drop in the gain observed in the entire WiFi band of 2.38–2.48 GHz amounts to 3.5 dB for the 0°/0° direction and 4.5 dB for the 0°/30° direction.

Field testing of the proposed antenna system was carried in the regime of wireless communications between two sites on the roofs and upper stories of office buildings and living houses in a city (Nizhni Novgorod) and between several sites of two cities separated by a big river (Volga), spaced by distances up to 7 km. Figure 3 shows a scheme of channels for communications across the river. The experiment consisted in tuning the directivity pattern of antenna (*1*) to a signal source (*2*, *3*, or *4*), followed by setting communication according to the IEEE 802.11b (WiFi) protocol and measuring the rate of data transfer using the proposed antenna. For measuring the transfer capacity of the communication channel, the antennas were connected to wireless communicators of the Gateworks Avila Network Processing System (GW2348-4) with network adapters 600 mV Ubiquity XR2 802.11bg. Transmission of a randomly generated 10-Mb data file according to the TCP/IT protocol from site *1* (office building) to distant sites *2* (hospital), *3* (school), and *4* (private house) with the transfer time monitored for different frequency channels allowed the transfer capacity of a system with the proposed antennas to be estimated as 6.17–7.53 Mbps (6.85 Mbps ± 10%).

Thus, we have demonstrated the possibility of creating a high-gain antenna with steerable directivity pattern based on a mirror formed by dipole scatterers with tunable parameters. Due to a simple antenna design with a minimum number of microwave elements, it is hoped that reflect-array antennas of this type can be effectively used in modern large-scale wireless communication systems.

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Translated by P. Pozdeev