11.1

Ku-band antenna array based on Fabry–Perot cavity

© S.V. Polenga, E.A. Litinskaya, A.V. Stankovsky, R.O. Ryazantsev, A.M. Alexandrin, E.P. Gafarov, A.A. Erokhin, Yu.P. Salomatov

Siberian Federal University, Krasnoyarsk, Russia
E-mail: twinlive@gmail.com

Received March 7, 2023
Revised April 24, 2023
Accepted May 2, 2023

The work is devoted to the development and study of the antenna array based on Fabry–Perot cavity in the radio band. The antenna array element in the form of a Fabry–Perot cavity with circular polarization is proposed, the semitransparent mirror of the cavity is realized in the form of a two-layer frequency-selective surface (FFS). A power divider based on thin waveguides to feed the antenna array with size 2×8 was developed. A model of the antenna array was manufactured. The power divider is made by laser cutting of sheet aluminum, semitransparent resonator layer is made by photolithography. The total efficiency of the antenna array was about 50% in the 5% frequency band with a VSWR of no more than 1.5.

Keywords: Fabry–Perot cavity, antenna array, satellite communication.

DOI: 10.61011/TPL.2023.07.56434.19550

Rapid progress in satellite communications and commissioning of new satellite constellations in the last few years specify additional requirements to ground satellite communication terminals. New satellite constellations „Express-RV“ and „Skif“ are not geostationary and require constant satellite tracking even from stationary terminals. Satellite terminals based on parabolic mirrors with mechanical scanning often fail to satisfy the requirements as to the antenna system profile and have a limited beam motion rate.

Although antennas based on foreign specialized microchips (Beamformer) provide fine performance and have a relatively small profile, the current high cost of components makes these devices too expensive for an average consumer.

The present study is focused on the design of a low-profile antenna system with a low fabrication cost for satellite communication terminals with mechanical scanning.

A Fabry–Pérot cavity is the most basic type of an optical cavity made up of two co-axial parallel mirrors facing each other. A resonance standing optical wave may form between them. In laser technology, one mirror is often made semitransparent for radiation to be output in the corresponding direction. Fabry–Pérot cavities operating in the radio-frequency range have been studied extensively in the last decade. While having a relatively simple design, a radiator based on a Fabry–Pérot cavity provides a high efficiency. The gain of individual cavities is as high as 17–20 dBi at an efficiency of 60–80% [1–4]. Although the gain increases with cavity size, the radiator efficiency decreases due primarily to a reduction in the efficiency of operation of the peripheral part of a larger cavity. The key drawback of a Fabry–Pérot cavity is its narrow bandwidth (the resonance condition is established at one frequency only). If a special frequency-selective surface (FSS) with a positive reflection phase gradient [4,5] is used as a semitransparent mirror, the resonance condition may be satisfied within a fairly wide frequency range that is sufficient for certain communication systems. Cavities with a bandwidth of 30% and more have been demonstrated [6,7], but their efficiency is at the level of 20–40%. No reports on cavities with a bandwidth in excess of 10% and an efficiency greater than 50% have been published. In the present study, the existing design of a Fabry–Pérot cavity operating with linear polarization [4] and having an efficiency of approximately 60% within the frequency band from 12 to 12.7 GHz was taken as a basis. This element features low phase and amplitude aperture distortion. It was proposed to use a short-circuit planar rectangular waveguide with two L-shaped slots in the broad face (Fig. 1, a) to feed the pre-designed cavity with circular polarization. This feed arrangement provided an ellipticity in excess of 0.8 and a voltage standing-wave ratio no greater than 1.5 within the operating frequency band. The semitransparent mirror was a two-layer FSS with a positive reflection phase gradient.

A 2×8 antenna array was constructed based on this radiator (Fig. 1, b). The array pitch was approximately 3.8λ, since this radiator size turned out to be the optimum one in terms of efficiency. A power divider based on thin waveguides was constructed to feed the cavities in the array. This divider was engineered with a view to minimize losses, dimensions, and the fabrication cost. The designed feed circuit contains five planar aluminum layers with their topology defined by laser cutting. Radiators are positioned in the first layer (Fig. 2, a); the second layer features two stages of binary power dividers; the third layer contains transition slots from the fourth layer to the second one; two stages of binary power dividers are located in the fourth layer; the input port is positioned in the fifth layer. A transformer matching the antenna input to a standard WR75 waveguide was constructed from seven planar aluminum

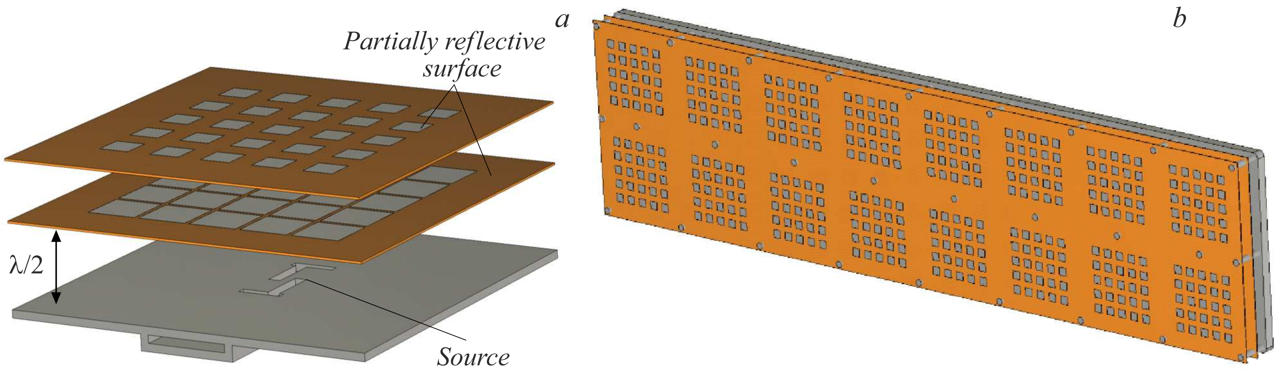

Figure 1. *a* — Structure of the Fabry–Pérot cavity; *b* — model of the antenna array based on Fabry–Pérot cavities.

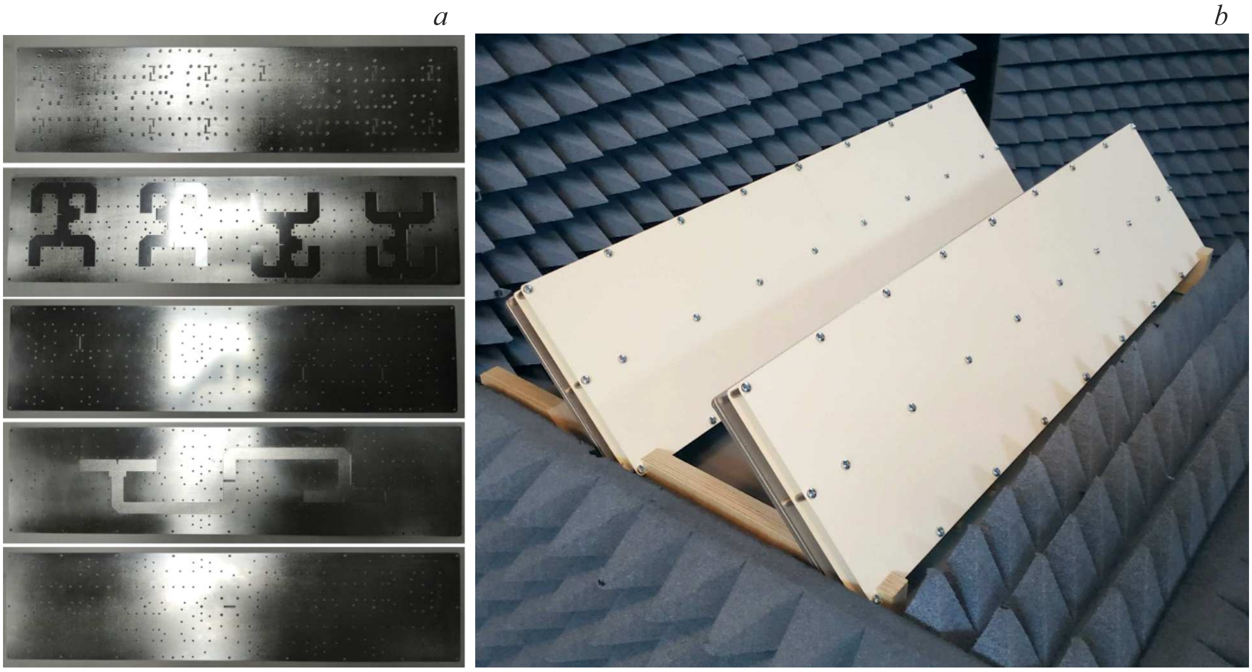

Figure 2. *a* — layers of the power divider of the antenna array; *b* — prototype models of antenna arrays based on Fabry–Pérot cavities.

plates of a varying thickness prepared by laser cutting. The power divider layers were held together by M3 screws. The overall thickness of the power divider and the entire antenna array was 9 and 38 mm, respectively. A two-layer FSS with its topology implemented by photolithography on Kappa 438 (a material similar to FR4, but with reduced losses, $\mathrm{tg}\,\delta = 0.005$) was located at a certain distance from the power divider. FSS layers were secured to spacers fabricated from an aluminum tube with an outer diameter of 6 mm; the error of spacer fabrication did not exceed $\pm 25\,\mu$m. Two prototype models of the antenna (Fig. 2, *b*) were produced simultaneously for their potential application in a venetian-blind antenna array [8] or in a single extended antenna array; a binary power divider was also fabricated for the purpose using the same techniques.

Measurements were performed by scanning the near antenna field with a planar scanner [9]. The nominal FSS height dimensions were corrected by no more than 0.2 mm to obtain characteristics close to the calculated ones. The need to correct the size of prototype models likely stems from the errors of fabrication of FSS circuit boards. In complete agreement with the results of calculations, the measured voltage standing-wave ratio within the 11.8–12.5 GHz band did not exceed 1.5.

The measured and calculated directivity patterns at a frequency of 12.5 GHz are shown in Fig. 3, *a*. A fairly high level of grating lobes in the $\pm 15^\circ$ direction is evident. This is attributable to a large array pitch and a non-uniform resulting amplitude aperture distribution. The grating lobes may be suppressed by equalizing the amplitude distribution, which may be done by reducing the size of cavities. However, the array efficiency will be reduced in this case due to the interaction of adjacent cavities. In addition, a greater number of radiators will be required to maintain

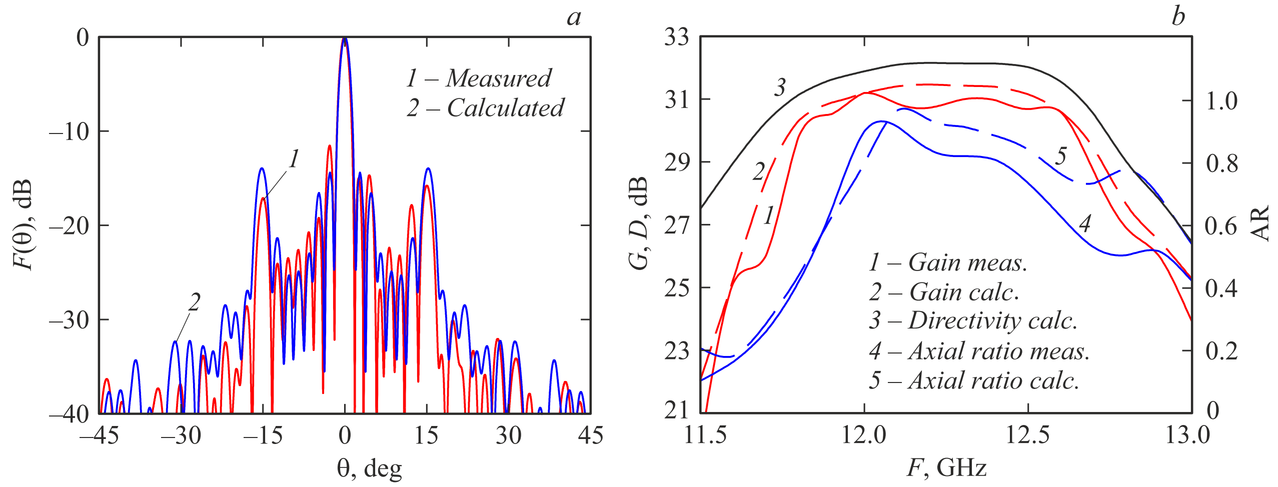

Figure 3. *a* — Measured and calculated directivity patterns of the antenna array in the horizontal plane; *b* — frequency dependences of the gain and the ellipticity.

the needed gain, and this will make the feed circuit more complex and increase the losses in it. The side radiation level in the vertical plane did not exceed -11 dB, and the width of the directivity pattern was approximately 7°. That said, the aperture efficiency of the antenna array was more than 60% within a bandwidth of about 5%. Figure 3, *b* shows the measured and calculated frequency dependences of the gain and the ellipticity. The overall losses in the power divider and the cavity, which were estimated by the difference between the antenna directivity and the gain (Fig. 3, *b*), were at the level of 1.1 dB. The resulting efficiency was approximately 50% within a 5% bandwidth. The measured ellipticity in the direction of the directivity pattern maximum turned out to be slightly higher than the calculated one and did not drop below 0.8 within the operating frequency band.

Thus, an antenna array designed in the present study has a small mass and thickness and may be constructed using domestically produced materials and equipment.

It was used successfully to receive the Ekspress-AT1 satellite signal in the Krasnoyarsk city area. A satellite converter was connected directly to the waveguide antenna output. In terms of the received signal level, the designed antenna corresponds to an offset mirror antenna 350 mm in diameter, which was used for comparison in field tests.

Funding

This study was supported financially by the Krasnoyarsk Regional Science Foundation as part of scientific project No. 2022102008915 „Antennas of Advanced Communications Networks for Application in the Far North“.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] Z.-H. Wu, W.-X. Zhang, IEEE Antennas Wireless Propag. Lett., **9**, 187 (2010). DOI: 10.1109/LAWP.2010.2045470

[2] Z.-H. Wu, W.-X. Zhang, IEEE Antennas Wireless Propag. Lett., **13**, 662 (2014). DOI: 10.1109/LAWP.2014.2314306

[3] A.M. Alexandrin, S.V. Polenga, A.V. Stankovsky, A.D. Nemshon, Y.A. Litinskaya, A.D. Hudonogova, Y.P. Salomatov, in *2016 Asia-Pacific Microwave Conf. (APMC)* (New Delhi, India, 2016), p. 1–4. DOI: 10.1109/APMC.2016.7931338

[4] M.I. Sugak, A.G. Zhuravlev, in *XI Vserossiiskaya nauchno-tekhnicheskaya konferentsiya „Elektronika i mikroelektronika SVCh“* (SPbGETU „LETI,“SPb., 2022), pp. 484–488 (in Russian).

[5] Y. Ge, K.P. Esselle, T.S. Bird, IEEE Trans. Antennas Propag., **60**, 743 (2012). DOI: 10.1109/TAP.2011.2173113

[6] Y. Guan, Y.-C. Jiao, J. Tian, X. Liu, Z. Cao, in *2020 Cross Strait Radio Science & Wireless Technology Conf. (CSRSWTC)* (Fuzhou, China, 2020), p. 1-3. DOI: 10.1109/CSRSWTC50769.2020.9372475

[7] S. Fang, L. Zhang, Y. Guan, Z. Weng, X. Wen, IEEE Antennas Wireless Propag. Lett., **22**, 412 (2023). DOI: 10.1109/LAWP.2022.3214230

[8] E.A. Litinskaya, S.V. Polenga, Yu.P. Salomatov, Izv. Vyssh. Uchebn. Zaved., Radioelektron., **24** (5), 36 (2021) (in Russian). DOI: 10.32603/1993-8985-2021-24-5-36-49

[9] A.S. Ivanov, K.V. Lemberg, S.V. Polenga, R.M. Krylov, Y.P. Salomatov, in *2015 Int. Siberian Conf. on control and communications (SIBCON)* (Omsk, Russia, 2015), p. 1–3. DOI: 10.1109/SIBCON.2015.7147334

Translated by D.Safin