ROCKET-SPACE DEVICE ENGINEERING AND INFORMATION SYSTEMS
Vol. 7, Iss. 4, 2020, pp. 91–95

The Principle of Formation of Metal-Dielectric Micro-Sized Metastructures

A.A. Adzhibekov, *rogov_ae@spacecorp.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
A.A. Zhukov, *Dr. Sci. (Engineering), Associate Prof., zhukov.aa@spacecorp.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation
FSBEI Moscow Aviation Institute (National Research University)
O. A. Alekseev, *Dr. Sci. (Engineering), Prof., centr31@spacecorp.ru*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation

Abstract. The principle of formation of layered metal-dielectric micro-sized metastructures, which are dielectric layers with deposited metal patterns, is proposed. The principle consists in the production of individual layers by photolithographic methods, followed by their assembly and alignment on a special installation using a source of high-frequency electromagnetic radiation with an antisymmetric field. The criterion for the accuracy of the alignment of layers is the power level of the received high-frequency electromagnetic signal at the output of the receiver, which fixes the field of the radiation source, scattered by the metal alignment marks applied to each matched layer. When applying the proposed principle, it is possible to combine optically opaque metal-dielectric layers of metastructures without the use of pins. A numerical assessment of the quality of layer alignment showed that the error of layer alignment when using a centimeter wavelength range for field sensing is no more than 3–4 μm.

Keywords: metamaterial, metastructure, waveguide

Introduction

Over the past two decades, many research groups have been actively studying the properties and determining the directions of application of metamaterials- composites with negative dielectric or (and) permeability. The first suggestion about the possibility of the existence of such materials was made in the work of V.G. Veselago [1]. Also in this work, the electrical properties of such materials were described theoretically using the apparatus of electrodynamics. Later, in [2, 3] the way of practical realization of such materials was shown. The publication of papers [2, 3] contributed to the intensification of research in this direction. The studies were aimed at studying the ways of realization of metamaterials and the directions of their potential applications. In particular, the possibility of using metamaterials for creating electrically small antennas, antennas with low back radiation, lenses, and screens with improved characteristics [4–7]. At the same time, the vast majority of publications reflect the realization of metamaterials in the form of layered metallodielectric composites. The size of the metal elements of these composites and the distance between the elements, as a rule, does not exceed the wavelength. Hence, as we move to higher frequency ranges, the implementation of metamaterials becomes increasingly difficult. In the millimeter and submillimeter wavelength ranges, the dimensions of metal elements can be tens to hundreds of microns, and the required tolerances for their fabrication are units of microns or less. Modern technologies for forming metallic structures on a dielectric substrate (lithographic fabrication methods) can provide such precision [8]. However, when creating a layered structure, there are difficulties with the exact positioning of the layers relative to each other. The issues of layer alignment during creation of miniature metal-dielectric structures are poorly studied at the moment. An analysis of openly available sources on this subject shows that high-precision alignment is usually required in the manufacture of multilayer printed circuit boards [9, 10]. The sources found show that for assembly and alignment in the technology of multilayer printed circuit boards, either pin assembly technology, which provides alignment errors of the order of ±50 μm, or automated assembly systems with an optical (X-ray) alignment system with errors of ±17 μm are used [9, 10]. In this regard, the actual task is to develop a principle of superposition of layered structures of metal-dielectric microdimensional metastructures that provides a high-precision (with a superposition error less than 5...10 μm) superposition of optically opaque layers without the use of pins.

The aim of the work is to develop a principle for the formation of layered metallodielectric microdimensional metastructures.

In order to achieve this goal, it is necessary to solve the following tasks:

- consider and analyze the use of electromagnetic radiation for the alignment of optically opaque layers;
- propose a hardware implementation of the principle - a quality control unit for the alignment of metastructure layers;
- perform a numerical evaluation of the quality of layer alignment.

Using electromagnetic radiation to align the layers

It is of interest to use electromagnetic radiation of centimeter, millimeter and submillimeter wavelength ranges for the alignment of layers of metal-dielectric microdimensional metastructures, which provides a high-precision alignment of layers without the use of pins. In this case, a simple irradiation of the coinciding metastructure layers by an electromagnetic field with subsequent study of the picture of its scattering to determine the quality of the coincidence of the layers seems to be unpromising. Firstly, probing the layered structure with waves of centimeter and even millimeter wavelength range with characteristic sizes of metallized elements of the order of tens of micrometers due to limitations on the diffraction limit will not provide an acceptable accuracy of matching. Second, each new type of layered structure will give its own complex and unique picture of electromagnetic radiation scattering. For each type of metastructure, this will require solving the problem of determining those scattering characteristics that can serve as criteria for the matching accuracy of the metastructure layers choosing the frequency range and the probe wave emitter parameters. At the same time, a single criterion for assessing the accuracy of layer alignment suitable for a wide class of metastructures is more acceptable for layer alignment technology. In this work, we propose to use a source of high-frequency electromagnetic radiation with an antisymmetric field to match the layers of metastructures [11]. Such a source can be, for example, the open end of a square waveguide with H11 or E11 mode. The picture of electric field field lines of these modes is shown in Fig. 1.

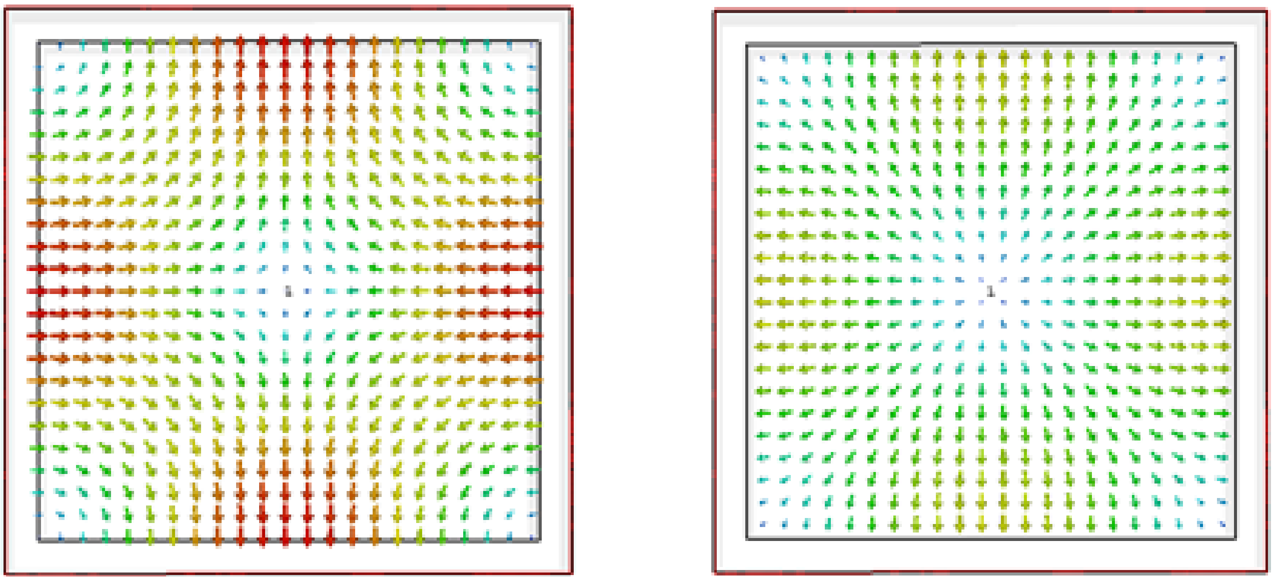

Fig. 1. Electric field lines of H11 (left) and E11 (right) in the cross section of the square waveguide.

Quality control unit for the alignment of metastructure layers

The scheme of the quality control unit for alignment of metastructure layers is shown in Fig. 2. The principle of the installation is as follows: on each dielectric layer with metallic metastructures a metallic alignment mark is formed, at the first stage of alignment the next layer is moved so that the alignment mark is in the space between two coaxial square waveguides. The frequency range used and the size of the waveguides are chosen so that in the waveguides in addition to the lower modes H10 and H01 can propagate modes H11 or E11. At the input of the first waveguide is connected transmitter and modes converter, providing the formation of the desired odd mode (H11 or E11), the second – the polarization selector providing selection of the lowest modes of the square waveguide. To the two outputs of the polarization selector there are connected receivers. Throttle structures and absorber serve to attenuate radiation flowing through the gap between the waveguides.

In the case where the label is perfectly aligned with the axis of the waveguides, symmetry must be preserved – the mode H11 or E11 passing through the dielectric layers with labels is partially reflected in the first waveguide, partially passes into the second, with the conversion of the odd mode to mode H10 or H01 does not occur. At the receiver outputs of the mode selector H10 and H01 in this case there are minima of signal power. If by any of the coordinate axes (x or y) is a shift of the label relative to the waveguide axis is a partial conversion of the odd mode in the H10 or H01 depending on the particular coordinate axis, which occurred shift. In this case, at the output of the corresponding channel of the mode selector there is an increase in signal power. The greater the shift, the greater the signal power of the corresponding channel. When there is a shift in both coordinate axes, the power increase in the channels of the polarization selector occurs simultaneously and mostly independently. Hence, the signals at the polarization outputs are actually the signals of errors of alignment along the x- and y-axes, these signals can be used by the system to align the layers. A similar setup can be used to match layers in the absence of rotations. To match layers in the presence of both shifts and rotations, two marks and two pairs of waveguides are required.

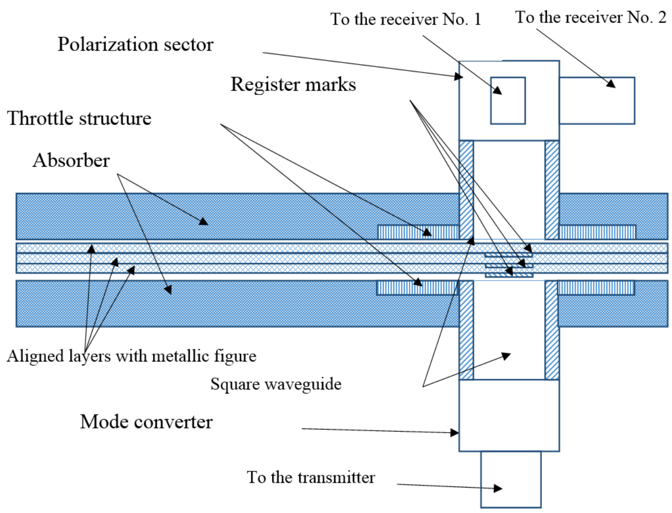

Fig. 2. The scheme of the quality control unit for the alignment of metastructure layers.

Results of the numerical evaluation of the quality of layer alignment

The results of the numerical evaluation of the quality of layer alignment using the proposed principle (dependences of the modules of the transmitter transmission coefficients into channels 1 and 2 of the polarization selector on the shifts along the x and y axes) are presented in Figs. 3–5. The evaluation was performed for two square waveguides with a width of 15 mm at 20 GHz. The matched structure was four dielectric layers with ε=2.2 and the thickness of 0.5 mm, with each layer labeled with the configuration shown in Fig. 6. During numerical calculation, we calculated the dependences of transmission coefficient modules from the input of the first waveguide to the channels of alignment errors along the x-axis and y-axis of the second waveguide on the shift of the layer closest to the receiving waveguide relative to the waveguide axis.

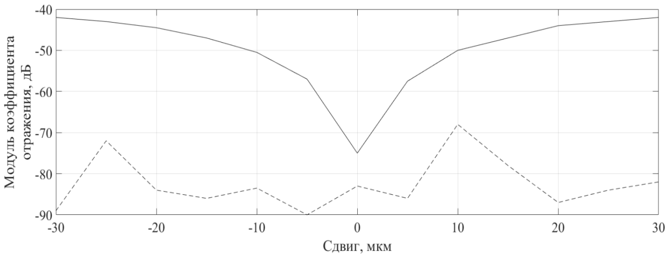

Fig. 3. Dependence of the transmission coefficient module of the first waveguide in the channels of errors of alignment along the x-axis (solid line) and the y-axis (dashed line) on the shift along the x-axis when there is no shift along the y-axis.

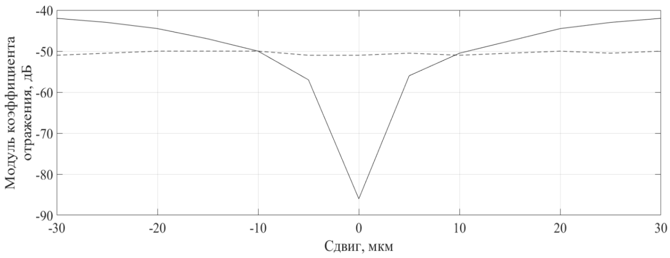

Fig. 4. Dependence of the transmission coefficient module of the first waveguide in the x-axis (solid line) and y-axis (dashed line) alignment error channels on the shift along the x-axis with a shift along the y-axis equal to 10 μm.

As can be seen from the figures, the minimum of the signals at the outputs No. 1 and No. 2 of the polarization selector corresponds to the case of perfect alignment. In this case, the signals of the alignment errors in the x- and y-axes are largely independent. At power of generated signal in 1 mW (0 dBmW), in case of both odd modes the value of signal power in the corresponding channel of alignment error at shift value of 3–4 μm will be not less than -57 dBmW. At the sensitivity of modern power meters, reaching -60 – -70 dBmW the magnitude of the received signal will be higher than the level of the power meter's own noise.

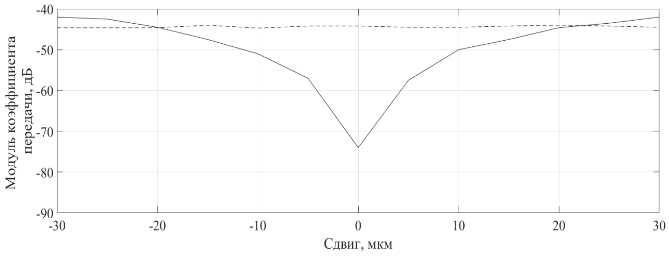

Fig. 5. Dependence of the transmission coefficient module of the first waveguide in the channels of errors of alignment along the x-axis (solid line) and the y-axis (dashed line) on the shift along the x-axis with a shift along the y-axis equal to 20 μm.

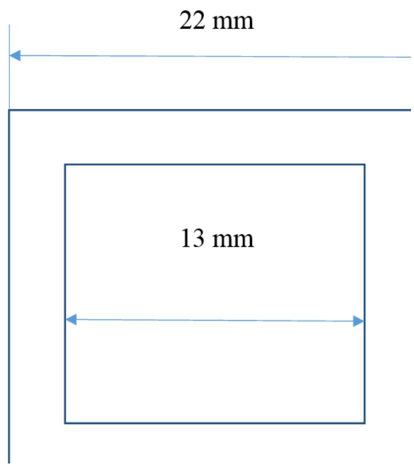

Fig. 6. The configuration of alignment marks.

Conclusion

Hence, the paper proposes the principle of creating layered metallodielectric metastructures, which consists in the fabrication of individual layers with a metallic pattern by photolithographic methods with their subsequent assembly and superposition into a layered structure. The criterion for alignment accuracy is the power level of the radiation source field incident on the receiver scattered by metal alignment marks applied to each layer to be aligned. The principle provides automated alignment of optically opaque metal-dielectric layers and does not require drilling holes or using pins. When using a probing electromagnetic field with a frequency of 20 GHz, the achievable error of alignment of layers is 3–4 μm. The obtained error is an order of magnitude smaller than the error of the pin technology and 3–4 times smaller than the error of the known X-ray method of alignment.

References

1. Veselago V.G. Elektrodinamika veshchestv s odnovremenno otritsatel'nymi znacheniyami ε i μ [Electrodynamics of substances with simultaneously negative values of ε and μ]. *Uspekhi fizicheskikh nauk,* 1967, Vol. 92, No. 3, pp. 517–526. (in Russian)
2. Pendry J.B. et. al. Magnetism from conductors and enhanced nonlinear phenomena. *IEEE Transactions Microwave Theory and Techniques*, 1999, No. 47, pp. 2075–2081.
3. Smith D.R. et al. Composite Medium with Simultaneously negative permeability and permitivitty. *Physical Review Letters,* 2000, Vol. 84, No. 18, pp. 4184–4187.
4. Slyusar V.I. Metamaterialy v antennoy tekhnike: istoriya i osnovannye printsipy [Metamaterials in antenna technology: history and underlying principles]. *Elektronika: nauka, tekhnologiya biznes* [Electronics: science, technology business], 2009, No. 7, pp. 70–79. (in Russian)
5. Slyusar V.I. Metamaterialy v konstruktsiyakh antenn [Metamaterials in antenna structures]. *Elektronika: nauka, tekhnologiya biznes* [Electronics: science, technology business], 2009, No. 8, pp. 66–70. (in Russian)
6. Slyusar V.I. Metamaterialy v antennoy tekhnike: osnovnye printsipy i rezul'taty [Metamaterials in antenna technology: basic principles and results]. *Pervaya milya* [First Mile], 2010, No. 3–4, pp. 44–60. (in Russian)
7. Vendik I.B., Vendik O.G. Metamaterialy i ikh primenenie v tekhnike sverkhvysokikh chastot (obzor) [Metamaterials and their application in microwave technology (review)]. *Zhurnal tekhnicheskoy fiziki* [Technical Physics Journal], 2013, Vol. 83, No. 1, pp. 4–28. (in Russian)
8. Valiev K.A. *Fizicheskie osnovy submikronnoy fotolitografii* [Physical foundations of submicron photolithography]. Moscow, Nauka, 1990, 350 p. (in Russian)
9. Cherkasov S. Oborudovanie firmy CEDAL EQUIPMENT dlya sborki i sovmeshcheniya paketov mnogosloynykh pechatnykh plat [CEDAL EQUIPMENT for assembling and aligning packages of multilayer printed circuit boards]. *Pechatnyy montazh* [Printed montage], 2006. No. 4, 6 p. Available at http://www.circuitry.ru/files/ article_pdf/2/article_2442_337.pdf (accessed October 30, 2020) (in Russian)
10. Shuvaev P.V. et. al. Formirovanie struktury slozhnykh mnogosloynykh pechatnykh plat [Formation of the structure of complex multilayer printed circuit boards]. *Trudy mezhdunarodnogo simpoziuma "Nadezhnost' i kachestvo"* [Proceedings of the International Symposium "Reliability and Quality"], 2013, pp. 364–373. (in Russian)
11. Adzhibekov A.A., Zhukov A.A., Alekseev O.A. Eksperimental'nyy stend dlya sborki i ispytaniy antennykh moduley na osnove mikrominiatyurnykh sloistykh metamaterialov [Experimental stand for assembly and testing of antenna modules based on microminiature layered metamaterials]. *Trudy MAI* [Proceedings of the MAI], 2016, No. 87, p. 14. (in Russian)