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(54) **MICROWAVE DIPLEXER FOR MINIATURE SATELLITES**

(57) A microwave diplexer intended for miniature satellites incorporates an antenna port (1), a transmitting port (2), a receiving port (3), and a transmitting filter (4) in between the transmitting port (2) and the antenna port (1), as well as a receiving filter (5) in between the receiving port (3) and the antenna port (1). All ports (1, 2, 3) and both filters (4, 5) of the diplexer are shaped on a single common printed circuit board (10) featuring a dielectric substrate (11) with the first and second metallization layer (12, 13) on its both sides, and metal delimiting structures (14) on the side walls of the printed circuit board (10). The transmitting filter (4) and the receiving filter (5) are band-pass filters of the substrate-integrated waveguide structure, and each of the filters is formed of hexagonal cavities (20) delimited with metallization layers (12, 13) of the printed circuit board (10) and the side walls in the form of metallized via-holes (15) between the metallization layers (12, 13). The hexagonal cavities (20) are connected to one another with windows (31) in the lines of metallized via-holes (15) and non-conducting slots (32) in the metallization layers (12, 13), where the slots are formed on the selected neighbouring side walls of the hexagonal cavities (20). The antenna port (1), transmitting port (2), and receiving port (3) take the form of coplanar lines formed on the printed circuit board (10) between its edges and the side walls of the hexagonal cavities (20), where the walls serve as the inlets and outlets for both filters (4, 5). The coplanar lines are connected with these hexagonal cavities (20) via the inlet slots (33) in the form of non-conducting lines in the metallization layer, where the transmitting filter (4) and the receiving filter (5) are separated from each other with an electromagnetic barrier in the form of complementary lines of metallized via-holes (15).

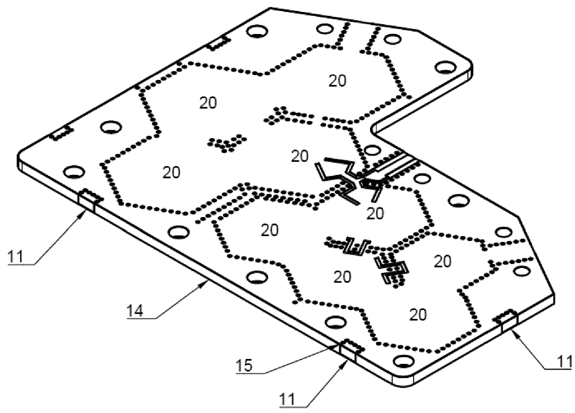

Fig. 2

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Description

[0001] The invention concerns a microwave diplexer for miniature satellites. The solution is designed for application in the radio path for communication between the Earth and the satellite, and also between individual satellites. In particular, the invention is designed for miniature satellites of the CubeSat standard structure, in particular nanosatellites for exploration of space and Earth observations.

[0002] Diplexers are systems enabling the use of a common communication path by two devices, in particular a transmitter and receiver, which transmit signals at different frequency channels, so that they can cooperate with the same antenna. The function is achieved by separating the transmitting frequencies from the receiving frequencies with filters. The diplexer incorporates a transmitting filter fitted between the transmitting port and the antenna, and a receiving filter fitted between the antenna and the receiving port. The type of the filters and the technology by which they are made depends on the place of application, the frequency ranges used, as well as the signal strength levels and the required transmission parameters.

[0003] Known from patent description US8130063B2 is a waveguide bandpass filter for use in satellite devices and microwave signals. The filter is made by the SIW technology, i.e. the substrate integrated waveguide technology. It is composed of several multimode rectangular cavities adjacent to one another and interconnected via slots, formed in a dielectric board with a metal layer on both sides and metalized via-holes. Microstrip lines or coplanar lines are used as filter input and output feeds.

[0004] Also known is a substrate integrated waveguide filter disclosed in patent description EP3236530B1. It is formed of dielectric substrate having metallic coating layers on both sides, metalized via-holes between the coating layers, and metalized side walls. One of the two flat metalized sides has insulated regions, wherein the individual insulated region features a specific number of via-holes. Present in the solution is a removable metallic cover for covering the metallic coating with the insulated regions. Depending on the use of the cover, the filter enables two functions: a filtering function, where the cover contacts the metallic coating, or the transmission function, where the metallic coating is not covered by the cover.

[0005] Known from the patent description published under No. CN112072224A is a balance bandpass filter built based on the technology of a substrate integrated waveguide SIW. It comprises four rectangular single-mode SIW resonators, one rectangular dual-mode SIW resonator, a pair of balance input feeders and a pair of balance output feeders. The input feeders and the output feeders are connected, as appropriate, with the single-mode resonators. The dual-mode resonator is located in the centre, and the four single-mode resonators are distributed around it and coupled therewith, as appropriate.

[0006] Presented in the international patent application published under number WO2022147627A1 is a filtering system featuring four ports and crossover transmission lines, made by the substrate-integrated waveguide [SIW] technology, with input/output feeds in the form of microstrip lines. It incorporates a single rectangular dual-mode cavity delimited with metalized via-holes, and a plurality of rectangular single-mode cavities arranged around the dual-mode cavity, where the single-mode cavities are delimited with metalized via-holes, and where at least one single-mode cavity is connected with the dual-mode cavity. Appropriate transmission lines are achieved by appropriate slot connection between the cavities. In one of the variants, one transmission line is made up of a rectangular dual-mode cavity and four (out of the total of eight) single-mode cavities located around the dual-mode cavity, while the second transmission line is made up of the rectangular dual-mode cavity and the remaining four single-mode cavities. In each variant of the solution, the same rectangular dual-mode cavity is shared by the first and second transmission lines and forms their crossover point.

[0007] Known from patent description No. KR101514155B1 is a waveguide diplexer for electromagnetic waves of the frequencies within the X and K_u bands. It incorporates a central pipe waveguide partially of the stepped structure formed by parallel combination of at least one rectangular parallelepiped featuring a via-hole formed longitudinally so that it matches its centre in the longitudinal direction. It also incorporates a waveguide connecting element in the shape of a rectangular parallelepiped featuring a via-hole formed longitudinally, where the connecting element is connected with the central waveguide so as to achieve the T-shaped structure of the magnetic field, thanks to which the electromagnetic waves of the X band (7.25 to 8.4 GHz) and Ku band (12.25-14.5 GHz) are branched.

[0008] Disclosed in the patent description published under No. CN110289468A is a diplexer for systems of satellite communication, mobile communication, and Internet of Things systems. The diplexer features a transmitting port, a receiving port, common antenna port and two filters in between the ports: a transmitting filter and receiving filter. The diplexer is built of rectangular and circular waveguides and passages in between them. In that diplexer, the reception path filter and the transmission path filter are located in a plane other than the common port. The connection between the waveguide filters and the antenna is located in the central part of the entire system, and the size of the connection with the antenna is substantially reduced. Proposed in the solution is an appropriate project of bending the filtering chamber space within the filter. The structure is more compact and smaller, while the insulation is higher. Thanks to it, it is possible to reduce the overall size of a ground satellite station.

[0009] Known are microwave filters of various types, made by the substrate-integrated waveguide technology, of various structures, and intended for different applications. Also known are various types of diplexers intended for various applications, made by different technologies, featuring various parameters, and incorporating bandpass filters: the transmitting and receiving ones. There are no known microwave diplexers with bandpass filters, in particularly designed for the X band, which would be suitable for being used in miniature satellites and which would satisfy the respective electric requirements and have the required dimensions or weight. Neither known are microwave diplexers with bandpass filters manufactured as a single structure of a substrate-integrated waveguide, which would be suitable for use in small satellite devices, the nanosatellites of the CubeSat type in particular.

[0010] The known solutions of waveguide diplexers, dedicated for various radio communication paths and various frequency channels in various devices, cannot be used in miniature satellites working in the X frequency band because they are too big and heavy.

[0011] A microwave diplexer intended for miniature satellites incorporates an antenna port, a transmitting port, a receiving port, and a transmitting filter in between the transmitting port and the antenna port, as well as a receiving filter in between the receiving port and the antenna port. According to the invention, the diplexer is characterised in that all ports and both filters are shaped on a single common printed circuit board featuring a dielectric substrate, the first and second metallization layer, and metal delimiting structures on the side walls of the printed circuit board. The transmitting filter and the receiving filter are bandpass filters of the substrate-integrated waveguide structure, and each of the filters is formed of hexagonal cavities delimited with printed circuit board metallization layers and the side walls in the form of metallized via-holes between the metallization layers. The hexagonal cavities are connected to one another with windows in the lines of metallized via-holes and non-conducting slots in the metallization layers, where the slots are formed on the selected neighbouring side walls of the hexagonal cavities. The antenna port, transmitting port and receiving port take the form of coplanar lines formed on the printed circuit board between its edges and the side walls of the hexagonal cavities, where the walls serve as inlets and outlets for both filters and are connected with the hexagonal cavities via inlet slots in the form of non-conducting lines in the metallization layer. In the diplexer according to the invention, the transmitting filter and the receiving filter are separated from each other with an electromagnetic barrier in the form of complementary lines of metallized via-holes.

[0012] Preferably, the receiving filter is formed of four hexagonal cavities in the shape of regular hexagons connected to one another with windows in their neighbouring side walls, sequentially starting from the first hexagonal cavity connected with the receiving port, following to the second and third hexagonal cavity, and up to the last, fourth hexagonal cavity connected with the antenna port. In addition, the hexagonal cavities of the receiving filter are connected via the windows between the second hexagonal cavity and the fourth hexagonal cavity, and between the first hexagonal cavity and the fourth hexagonal cavity, where the windows are formed in the neighbouring side walls of the cavities. The transmitting filter is formed of five hexagonal cavities in the shape of regular hexagons sequentially connected to one another via windows in their neighbouring side walls, starting from the fifth hexagonal cavity connected with the transmitting port, through the sixth, seventh, and eighth hexagonal cavity, and up to the last ninth hexagonal cavity connected with the antenna port. The hexagonal cavities of the transmitting filter are also connected via non-conducting slots between the fifth hexagonal cavity and the seventh hexagonal cavity, and between the seventh hexagonal cavity and the ninth hexagonal cavity, where the slots are formed in their neighbouring side walls.

[0013] Preferably, the hexagonal cavities of the receiving filter form the shape of a fragment of a four-cell honeycomb and are arranged along two perpendicular axes, while the hexagonal cavities of the transmitting filter form the shape of a fragment of a five-cell honeycomb, with the fifth and ninth hexagonal cavity arranged in one row, and the sixth, seventh, and eighth hexagonal cavity arranged in another row underneath, parallel thereto, where one of the side walls of the eighth hexagonal cavity in the transmitting filter neighbours on the side wall of the third hexagonal cavity in the receiving filter, and another of its side walls on the side wall of the fourth hexagonal cavity in the receiving filter, and where one of the side walls of the ninth hexagonal cavity neighbours on the side wall of the fourth hexagonal cavity.

[0014] Even more preferably, the non-conducting slots between the hexagonal cavities take the form of five-section broken lines of the "omega" shape and are shaped on both metallization layers, where located on the second metallization layer under each non-conducting slot in the first metallization layer is a corresponding non-conducting slot in mirror reflection.

[0015] In a preferable embodiment, the inlet slot of the transmitting port and the inlet slot of the receiving port take the form of two non-conducting lines formed on both sides of the conducting strips of the coplanar lines, where the said non-conducting lines are bent twice in the hexagonal cavity at the right angle, forming the shape of a cylindrical chalice opening towards the inside of the cavity. The inlet slots of the antenna port are composed of three non-conducting lines, where two of them are given the shape of broken lines starting with two non-conducting lines shaped on both sides of the conducting strip of the coplanar line, where one of the said non-conducting lines ends inside the ninth hexagonal cavity of the transmitting filter, the second non-conducting line ends inside the fourth hexagonal cavity of the receiving filter, and the third non-conducting line forms a broken line between the ninth hexagonal cavity of the transmitting filter and the fourth hexagonal cavity of the receiving filter. Inside the ninth hexagonal cavity and the fourth hexagonal cavity, the inlet slots take the form of a conical chalice narrowing down and opening towards the inside of the cavities.

[0016] Particularly preferably, the antenna port is situated in the central part of the printed circuit board and is connected with the neighbouring side walls of the fourth hexagonal cavity in the receiving filter and the ninth hexagonal cavity in the transmitting filter, while the transmitting port and the receiving port are situated on opposite sides of the antenna port, where the transmitting port is connected with the side wall of the fifth hexagonal cavity, the wall being opposite with respect to the same cavity's side wall neighbouring on the side wall of the seventh hexagonal cavity, and the receiving port is connected with the side wall of the first hexagonal cavity opposite its side wall neighbouring on the side wall of the fourth hexagonal cavity.

[0017] Most preferably, the transmitting port and the receiving port are formed on the first metallization layer, while the antenna port is shaped on the second metallization layer, where the transmitting port axis and the receiving port axis are positioned at an angle larger than 20° with respect to the axis of the antenna port.

[0018] In a preferable variant, the printed circuit board features three microwave coaxial connectors integrated, respectively, with the antenna port, transmitting port, and receiving port, and is fitted in a metal casing composed of a body which contacts the first metallization layer and a cover which contacts the second metallization layer, where the body and the cover feature shaped empty chambers over the non-conducting slots, and separate empty chambers over the inlet slots, they also feature connecting holes and mounting holes.

[0019] Even more preferably, the coplanar lines are of minimum length required for their integration with the microwave coaxial connectors, and the printed circuit board takes the shape of a polygon incorporating all hexagonal cavities and all ports, where the minimum dimensions of the board ensure its integration with the body and the cover.

[0020] Also preferably, the casing features ventilation openings and additional openings.

[0021] In one of the diplexer variants designed for application in CubeSate nanosatellites of standardised dimensions, the body of the casing is larger than the outline of the printed circuit board and takes the shape of a square plate the side of which is 10 cm long or shorter, and the cover covers only the central part of the printed circuit board with the antenna port, non-conducting slots between the hexagonal cavities, and the inlet slots of the antenna port.

[0022] In a preferable embodiment variant intended for specific frequency channels, the dimensions of the hexagonal cavities, the metallized via-holes, windows, non-conducting slots, inlet slots, and coplanar lines are designed and configured so that they transmit, through the transmitting filter, the frequencies of the X band ranging from 8025 to 8500 MHz, and through the receiving filter the frequencies of the X band ranging from 7145 to 7250 MHz, with the quality factor above 450 and insulation between the transmission channel and the reception channel above 80 dB.

[0023] The microwave diplexer according to the invention solves the problem of simultaneous transmission of microwave signals and reception signals in the X band in the radio path of a miniature satellite device, between the common antenna and the transmitting-and-receiving system, using a single system being a structure shared by the transmission path and the reception path. The signals can be sent simultaneously along both paths without the need to switch between them during the transmission, while ensuring the required transmission parameters and very good insulation between the transmission path and the reception path, where the insulation protects the input circuits of the receiver from saturation during the transmission. At the same time, the solution according to the invention guarantees high miniaturization, small weight, the required electromagnetic tightness, and resistance to breakdown in vacuum. This is particularly important in the case of miniature artificial satellites, including nanosatellites of the CubeSat type of standardized dimensions, which require the smallest possible weight and dimensions of the systems placed therein, and which are characterized by high differences in the power levels between the transmission and reception signals.

[0024] An exemplary embodiment of the solution according to the invention is illustrated with a drawing, in which Fig. 1 presents the diplexer topology, Fig. 2 shows an axonometric view of the printed circuit board of the diplexer, Fig. 3 presents the view of the diplexer printed circuit board from the side of the first metallization layer, Fig. 4 shows the view of the diplexer printed circuit board from the side of the second metallization layer, Fig. 5 depicts the view of the diplexer casing from the side contacting the printed circuit board, Fig. 6 presents an axonometric view of the diplexer with connectors and in the casing, from the side of the first metallization layer, Fig. 7 shows an axonometric view of the diplexer with connectors and in the casing, from the side of the second metallization layer, Figures 8, 9, 10 show three cross-sections of the diplexer with the casing and connectors, in axonometric views, Fig. 11 depicts a fragment of the diplexer cross-section with the casing at the point where the microwave connection is mounted, and Figures 12 - 17 show diagrams of the transmission characteristics between the diplexer ports.

[0025] In the exemplary embodiment of the invention, the microwave diplexer for miniature satellites features three ports **1, 2, 3** and two filters **4, 5.** The ports are intended for introducing the diplexer into the transmission path TX and the reception path RX in the radio path of a satellite device working in the X frequency band, between the transmitting-and-receiving system and the transmitting-and-receiving antenna. The antenna port **1** is intended for connecting the diplexer to the antenna of the satellite device, the transmitting port **2** is intended for connecting the diplexer to the outlet of the transmitting system in the satellite device, and the receiving port **3** is intended for connecting the diplexer to the inlet of the receiving system in the satellite device. The transmitting filter **4** and the receiving filter **5** are bandpass filters, which ensure simultaneous bi-directional communication in X band frequencies between the satellite and the Earth, or between satellites. All elements of the diplexer, three ports and two filters, are shaped on a single common printed circuit board **10** composed of a dielectric substrate **11,** the first metallization layer **12** on one side of the dielectric substrate **11** and the second metallization layer **13** on the other side of the dielectric substrate **11.** The side walls of the printed circuit board **10** feature metal limiting structures **14** formed by metallization of the walls. At points where technological aspects make it impossible to achieve continuous metallization layer, the metal limiting structures **14** are formed as additional metallized via-holes **15** in the printed circuit board **10,** as shown in Fig. 2. The metal limiting structures **14** serve as an electromagnetic barrier for the signals propagated in the structure of the printed circuit board **10.** The transmitting filter **4** and the receiving filter **5** are shaped on the printed circuit board **10** as substrate-integrated waveguides, and the antenna port **1,** transmitting port **2,** and receiving port **3** are shaped on the same printed circuit board **10** in the form of straight sections of coplanar lines. Each of the filters is composed of resonators in the form of hexagonal cavities **20** connected to one another and integrated with the substrate, where the top and bottom wall are formed by the first metallization layer **12** and the second metallization layer **13,** and the side walls of the hexagonal cavities **20** are formed as metallized lines of via-holes **15** between the said layers. Each of the hexagonal cavities **20** is limited with lines of metallized via-holes **15** forming the shapes of regular hexagons. The hexagonal cavities **20** are interconnected via windows **31** which break the lines of the via-holes, and via non-conducting slots **32** in the form of non-conducting paths in the metallization layers. The windows **31** and the non-conducting slots **32** form inductive couplings and capacitive couplings, respectively, between filter resonators in the form of hexagonal cavities **20** of the substrate-integrated waveguide. Also found on the printed circuit board **10** are inlet slots **33** in the form of non-conducting lines in the metallization layer, which form electric inlet/outlet couplings between the ports and filters. The receiving filter **5** takes the form of four hexagonal cavities **21, 22, 23, 24** identical in size, arranged in the shape of a four-cell honeycomb along two perpendicular axes: in the view from the side of the first metallization layer **12** and then subsequently clockwise, from the first, through the second and third, up to the fourth, as shown in Fig. 3. In the first hexagonal cavity **21,** on one of the side walls which form the outlet of the receiving filter **5** there is an entry slot **33** formed on the first metallization layer **12,** where the slot **33** takes the form of two parallel non-conducting lines on the one side connected to the non-conducting strips of the coplanar line shaped on the same metallization layer and forming the diplexer receiving port **3,** and on the other side to the lines bent twice at the right angle, which form the shape of a cylindrical chalice opening towards the inside of the hexagonal cavity **21** inside the same hexagonal cavity. The first hexagonal cavity **21** is inductively coupled with the second hexagonal cavity **22** and the fourth hexagonal cavity **24** via windows **31** on their neighbouring side walls. The second hexagonal cavity **22** is inductively coupled via windows **31** in their neighbouring side walls with the third hexagonal cavity **23** and the fourth hexagonal cavity **24,** which at the same time is inductively coupled with the third hexagonal cavity **23** via window **31** in their neighbouring side walls. The transmitting filter **4** is formed of five hexagonal cavities **25, 26, 27, 28, 29** arranged in the shape of a five-cell honeycomb in two rows, where its view from the side of the first metallization layer **12** is shown in Fig. 3: the fifth hexagonal cavity **25** and the ninth hexagonal cavity **29** are arranged in a single row, while the sixth, seventh, and eighth hexagonal cavity **26, 27, 28** are arranged underneath. Formed on the first metallization layer **12** in the fifth hexagonal cavity **25,** on one of its side walls forming the inlet of the transmitting filter **4,** is an inlet slot **33** in the form of two parallel non-conducting lines, on the one end connected to the non-conducting strips of the coplanar line shaped on the same metallization layer and forming the transmitting port **2** of the diplexer, and on the other end bent twice at the right angle to form the shape of a cylindrical chalice opening towards the fifth hexagonal cavity **25** inside that hexagonal cavity. The hexagonal resonators of the transmitting filter **4** are inductively coupled to one another via windows **31**, subsequently from the fifth hexagonal cavity **25** through the sixth, seventh, and eighth hexagonal cavity **26, 27, 28** up to the ninth hexagonal cavity **29,** where the windows are found in the neighbouring side walls of the resonators. At the same time capacitively coupled with one another via non-conducting slots **32** on the metallization layers are: the fifth hexagonal cavity **25** with the seventh hexagonal cavity **27,** and the seventh hexagonal cavity **27** with the ninth hexagonal cavity **29,** where the slots are found in the neighbouring side walls of the cavities. The non-conducting slots **32** are found on both metallization layers **12, 13** and each of them forms a five-section line broken at the right angle to form the "omega" shape. Under each non-conducting slot **32** on the first metallization layer **12** is a corresponding non-conducting slot **32** on the second metallization layer **13,** which represents a mirror reflection along the normal plane with respect to the board, as shown in Fig. 3 and Fig. 4. The transmitting filter **4** and the receiving filter **5** are arranged on the printed circuit board **10** side by side, so that one of the side walls of the third hexagonal cavity **23** neighbours on the eighth hexagonal cavity **28,** and two side walls of the fourth hexagonal cavity **24** neighbour on the ninth hexagonal cavity **29.** The coplanar line of the antenna port **1** is found in the central part of the printed circuit board **10** on the second metallization layer **13,** and the coplanar lines of the transmitting port **2** and the receiving port **3** are found on the first metallization layer **12,** on opposite sides of the antenna port **1.** The axes of the transmitting port **2** and the receiving port **3** are tilted away from the axis of the antenna port **3** at the angle of 30°. Formed in the central part of the printed circuit board **10,** on the neighbouring side walls of the fourth and ninth hexagonal cavities **24, 29,** on the second metallization layer **13,** are inlet slots **33** connected with the antenna port **1** of the diplexer. They are formed of three non-conducting lines. Two of them are given the shape of broken lines starting with two non-conducting lines shaped on both sides of the conducting strip of the coplanar line forming the antenna port **1,** where one of them ends inside the ninth hexagonal cavity **29** of the transmitting filter **4,** and the other one ends inside the fourth hexagonal cavity **24** of the receiving filter **5.** The third non-conducting line forms a broken line between the ninth hexagonal cavity **29** of the transmitting filter **4** and the fourth hexagonal cavity **24** of the receiving filter **5,** where the inlet slots **33** inside these hexagonal cavities **24, 29** are given the shape of a conical chalice narrowing down and opening towards the inside of the fourth hexagonal cavity **24** and the ninth hexagonal cavity **29,** as shown on Fig. 4. The inlet slots **33** form electric couplings between the diplexer ports and filters. There are complementary lines of metallized via-holes **15** between the other neighbouring side walls of the hexagonal cavities of the transmitting filter **4** and the hexagonal cavities of the receiving filter **5.** In this way both filters are separated from each other with an additional electromagnetic barrier. In the exemplary embodiment each of the ports **1, 2, 3** of the diplexer is integrated with a microwave coaxial connector **40,** which enables connecting it to a transmitting-and-receiving antenna and the transmitting-and-receiving system of a satellite device. In the transmitting port **2** and the receiving port **3,** the hot pins of the microwave coaxial connectors **40** are soldered to the transmission paths of the coplanar lines on the first metallization layer **12.** In the antenna port **1,** the hot pin of the microwave coaxial connector **40** is soldered to the transmission path of the coplanar line on the second metallization layer **13.** The printed circuit board **10** with the diplexer and the microwave coaxial connectors **40** attached to the board are tightly fitted in a metal casing **50,** between its body **51** and cover **52.** The body and the beam which form the casing of each microwave coaxial connector **40** are found on the opposite sides of the printed circuit board **10** and are connected to the printed circuit board **10** and the casing **50** with two connector screws **41.** As shown in Fig. 6, 7, the body **51** of the casing **50** contacts the first metallization layer **12,** and the cover **52** of the casing **50** contacts the second metallization layer **13.** The body **51** and the cover **52** feature empty chambers **53** formed on the side of the printed circuit board **10** on its both sides, over the non-conducting slots **32** and over the inlet slots **33** together with the coplanar lines which form ports **1, 2, 3.** The empty chambers **53** over the non-conducting slots **32** are separated from the empty chambers **53** over the entry slots **33.** The body **51** features connecting holes **54** which accommodate the microwave coaxial connectors **40** extending outside the outline of the printed circuit board **10.** The printed circuit board **10,** as well as the body **51** and the cover **52** of the casing **50** feature mounting holes **55** which enable connecting these elements with one another using connector screws **41** and mounting screws **57.** In addition, the body **51** and the cover **52** feature small ventilation holes **58** in each empty chamber. Moreover, the body **51** and the cover **52** feature additional holes **59** of various shapes, which reduce the total weight of the casing **50.** In the exemplary embodiment, the body **51** of the casing **50** is largest in area and is given the rectangular shape. The printed circuit board **10** is smaller and is given the shape of a minimum polygon incorporating all hexagonal cavities **20**, the coplanar lines which form ports **1, 2, 3,** and the necessary mounting holes **55** on perimeter of the board. The cover **52** of the casing **50** is smallest in area, where the area incorporates its empty chambers **53** and the mounting holes **55** necessary for connecting it to the printed circuit board **10** and the body **51.** The empty chambers **53** over the inlet slots **33** and the coplanar lines are shaped so as to also accommodate the casings of the microwave coaxial connectors **40.** All mounting slots **57** between the first and second metallization layers **12, 13** of the printed circuit board **10** and the casings of the microwave coaxial connectors **40,** between the metal casing **50** of the diplexer and the casings of the microwave coaxial connectors **40** and between the metallized edges of the printed circuit board **10** and its metal casing **50,** are filled with a soldering material or any other electromagnetically tightening material.

[0026] In a satellite device, the diplexer according to the invention is introduced into the transmission path TX and the reception path RX of the microwave signals received and transmitted by a satellite, between the transmitting-and-receiving system and the antenna of the satellite device. The microwave transmission signal from the transmitting system of the satellite is introduced via the microwave coaxial connector **40,** the coplanar line which forms the transmitting port **2,** and the inlet slot **33** on the first metallization layer **12,** into the fifth hexagonal cavity **25** in the transmitting filter **4** of the diplexer. In the structure of the substrate-integrated waveguide which forms the transmitting filter **4,** inside its hexagonal cavities: fifth **25,** sixth **26,** seventh **27,** eighth **28** and ninth **29,** the microwave transmission signal is propagated as a single-mode electromagnetic wave and led out of the ninth hexagonal cavity **29** through its inlet slot **33** and via the grounded coplanar line which forms the antenna port **1** on the second metallization layer **13,** to the microwave coaxial connector **40,** from where it is transmitted to the antenna of the satellite device. The microwave reception signal from the antenna of the satellite device is introduced via the microwave coaxial connector **40,** the grounded coplanar line which forms the antenna port **1,** and the inlet slot **33** on the second metallization layer **13** into the fourth hexagonal cavity **24** in the receiving filter **5** of the diplexer. In the structure of the substrate-integrated waveguide which forms the receiving filter **5,** inside its hexagonal cavities: fourth **24,** third **23,** second **22,** and first **21,** the microwave reception signal is propagated as a single-mode electromagnetic wave and led out of the first hexagonal cavity **21** through its inlet slot **33** and the coplanar line which forms the receiving port **3** on the first metallization layer **12,** to the microwave coaxial connector **40,** from where it is transmitted to the receiving system of the satellite device. Proper separation and filtration of the signals of the transmission path and the reception path for specific frequencies is ensured by: the structure, shape, dimensions, and arrangement of the hexagonal cavities **20,** metallized via-holes **15,** windows **31** in the metallized via-hole lines **15,** and non-conducting slots **32** which form the transmitting filter **4** and the receiving filter **5,** the inlet slots **33,** the coplanar lines which form the antenna port **1,** the transmitting port **2,** the receiving port **3,** as well as by the materials and dimensions of the dielectric substrate **11** and the metallic layers **12, 13** of the printed circuit board **10.** The parameters of the diplexer and its functioning in the satellite device are also improved by its casing **50** where the empty chambers **53** therein enable the necessary couplings and closing of the space, thanks to which any undesirable seepages are reduced. At the same time, the body **51** of the casing **50** enables simple mounting of the diplexer within the skeletal structure of miniature satellites, in particular in nanosatellites of the CubeSat type.

[0027] In the exemplary embodiment, the printed circuit board **10** is given the shape of a polygon, where its longest edge, along the sixth, seventh, eighth, and third hexagonal cavities **26, 27, 28, 23** is 75 mm long, the first side edge perpendicular to it and running along the third, second, and first hexagonal cavities **23, 22, 21** is 50 mm long, and the second side edge perpendicular to it and running along the sixth and fifth hexagonal cavities **26, 25** is 30 mm long. The other edges of the printed circuit board **10** form a broken line along the side walls of the first, fourth, ninth, and fifth hexagonal cavities **21, 24, 29, 25** and along the coplanar lines, as shown in Fig. 3, 4. The terminal sections of the said broken lines are askew with respect to the side edges of the board, and the total length of the board perimeter is the minimum length necessary to cover the area of the filters, ports, and the mounting holes on the board. The body **51** of the casing **50** takes the form of a rectangular plate sized 95 mm x 91 mm with three empty chambers **53** separated from one another shaped thereon: one chamber over the non-conducting slots **32,** the second one over the transmitting port **2** and the inlet slot **33** of the transmitting filter **4,** and the third one over the transmitting port **3** and the inlet slot **33** of the receiving filter **5.** All of the remaining area of the body **51** adheres tightly to the first metallization layer **12.** The cover **52** is irregular in shape and is given the minimum dimensions required for it to tightly adhere to the second metallization layer **13** and for its permanent connection to the printed circuit board **10** and the body **51,** and to have two empty chambers **53** formed therein: one over the non-conducting slots **32** and the other one over the antenna port **1** and the inlet slots **33** linked to that port. Once the printed circuit board **10** together with the concentric microwave connectors **40** is mounted between the body **51** and the cover **52** of the casing **50,** the entire device is 13.5 mm in height. The longest straight edge of the printed circuit board **10** lines up with one of the casing edges, the microwave coaxial connectors **40** are found inside the connecting holes **54** of the body **51,** and the axes of the transmitting port **4** and the receiving port **5** are tilted at the angle of 30° with respect to the axis of the central antenna port **1.** Such arrangement of the ports **1, 2, 3** and the microwave coaxial connectors **40** minimises the electromagnetic seepages between the diplexer ports.

[0028] In the exemplary embodiment the diplexer has been designed to transmit microwave signals of frequencies within the range of 7145-7235 MHz in the reception path and 8350-8500 MHz in the transmission path. The casing **50** is made of aluminium and coated with a layer which enables soldering. The dielectric substrate **11** of the printed circuit board **10** takes the form of a microwave laminate characterised by losses DF<1.2E-4 and the thickness of 1.5 mm. The first and second metallization layers **12, 13** are made of rolled copper 0.035 mm thick, characterized by the average roughness of the side contacting the laminate below 0.4 μm. The casing **50** adheres to the bodies of concentric microwave connectors **40** with tolerances below 0.3 mm. The dimensions of the diplexer elements on the printed circuit board **10** are designed using the CAD/CAE software. The metallized via-holes **15** are 0.5 mm in diameter, they are spaced at the distance of 0.25 mm to one another, and positioned with an error below 50 μm. The side walls of each hexagonal cavity of the receiving filter **5** are ~10 mm in length, while the side walls of the hexagonal cavities of the transmitting filter **4** are ~8 mm in length. The non-conducting slots **32** and the inlet slots **33** are 0.5 mm wide. The lengths of the non-conducting slots on the metallization layers, and the widths of the windows in the metallized via-hole lines are diversified and were calculated by way of computer electromagnetic simulations using analytical formulas so as to achieve the required capacitive and inductive couplings between the hexagonal cavities **20** which form the resonators of filters **4, 5,** and between the ports **1, 2, 3** and filters **4, 5** of the diplexer, which ensures the expected parameters of the diplexer's transmission characteristics. The coplanar lines which form individual ports are minimum in length, which enables connection and mounting of microwave coaxial connectors **40,** which in the exemplary embodiment are the SMA connectors. All mounting slots **57** are filled with a soldering material in the form of the Sn60Pb40 alloy. The structure and distribution of filters **4, 5,** ports **1, 2, 3** and the structure of the printed circuit board **10** together with the connectors **40** and the casing **50** ensure very high electromagnetic tightness and minimize the undesirable electromagnetic seepages. The individual transmission features of the diplexer in its exemplary embodiment are shown on Fig. 12 - 17. The insulation between the transmission band and the reception band is over 80 dB, the shielding tightness to 18 GHz is over 30 dB, and over 60 dB in the working band. Another important parameter are insertion losses which do not exceed 1 dB in both bands. The diplexer structure according to the invention enables minimizing its overall dimensions and weight, while simultaneously ensuring the quality factor Q_u above 450. Moreover, the diplexer structure proves resistant to the effect of breakdown in vacuum up to the power level of 500 W thanks to the use of the substrate-integrated waveguide technology. In addition, the diplexer structure with the connectors and the casing ensures high mechanical resistance to impact and vibrations, necessary in equipment designed for use in space.

[0029] The diplexer according to the invention enables its placing in miniature satellite devices so as to transmit signals within the specific frequency channels in the radio path between the antenna and the transmitting-and-receiving system, in the correct directions, simultaneously in the transmission path TX and the reception path RX of a satellite device, whilst ensuring high level of separation between the transmission path TX and the reception path RX. The presented exemplary embodiment does not exhaust the possible variants of solution embodiments characterized by the determinant features according to the invention. The diplexer filters can be configured in various variants throughout the entire available range of microwave frequencies. In particular, possible are various variants of the arrangement, connections, and dimensions of diplexer elements on the common PCB board constituting structures of a substrate-integrated waveguide [SIW] with inlets/outlets in the form of coplanar lines. Different, too, can be the parameters of physical embodiment, depending on the specific application place, designation, requirements, and frequency ranges used in radio transmissions of microwave signals.

Claims

1. A microwave diplexer for miniature satellites, incorporating an antenna port (1), a transmitting port (2), a receiving port (3), and a transmitting filter (4) in between the transmitting port (2) and the antenna port (1), as well as a receiving filter (5) in between the receiving port (3) and the antenna port (1) **characterised in that** all ports (1, 2, 3) and both filters (4, 5) of the diplexer are shaped on a single common printed circuit board (10) featuring a dielectric substrate (11) with the first and second metallization layer (12, 13) on its both sides, and metal delimiting structures (14) on the side walls of the printed circuit board (10), where the transmitting filter (4) and the receiving filter (5) are bandpass filters of the substrate-integrated waveguide structure, and each of the filters is formed of hexagonal cavities (20) delimited with metallization layers (12,13) of the printed circuit board (10) and the side walls in the form of metallized via-holes (15) between the metallization layers (12, 13), and where the hexagonal cavities (20) are connected to one another with windows (31) in the lines of metallized via-holes (15) and non-conducting slots (32) in the metallization layers (12, 13), where the slots are formed on the selected neighbouring side walls of the hexagonal cavities (20), while the antenna port (1), transmitting port (2), and receiving port (3) take the form of coplanar lines formed on the printed circuit board (10) between its edges and the side walls of the hexagonal cavities (20), where the walls serve as the inlets and outlets for both filters (4, 5), where the coplanar lines are connected with these hexagonal cavities (20) via the inlet slots (33) in the form of non-conducting lines in the metallization layer, and where the transmitting filter (4) and the receiving filter (5) are separated from each other with an electromagnetic barrier in the form of complementary lines of metallized via-holes (15).

2. The diplexer according to Claim 1, **characterised in that** the receiving filter (5) is formed of four hexagonal cavities (21, 22, 23, 24) in the shape of regular hexagons connected to one another with windows (31) in their neighbouring walls, sequentially starting from the first hexagonal cavity (21) connected with the receiving port (3), following to the second and third hexagonal cavity (22, 23), and up to the last, fourth hexagonal cavity (24) connected with the antenna port (1); in addition, the cavities are connected via the windows (31) between the second hexagonal cavity (22) and the fourth hexagonal cavity (24), and between the first hexagonal cavity (21) and the fourth hexagonal cavity (24), where the windows are formed in the neighbouring side walls of the cavities, while the transmitting filter (4) is formed of five hexagonal cavities (25, 26, 27, 28, 29) in the shape of regular hexagons sequentially connected to one another via windows (31) in their neighbouring side walls, starting from the fifth hexagonal cavity (25) connected with the transmitting port (2), through the sixth, seventh, and eight hexagonal cavity (26, 27, 28), and up to the last ninth hexagonal cavity (29) connected with the antenna port (1), and also connected via non-conducting slots (32) between the fifth hexagonal cavity (25) and the seventh hexago-

nal cavity (27) and between the seventh hexagonal cavity (27) and the ninth hexagonal cavity (29), where the slots are formed in their neighbouring side walls.

3. The diplexer according to Claim 2, **characterised in that** the hexagonal cavities (21, 22, 23, 24) of the receiving filter (3) form the shape of a fragment of a four-cell honeycomb and are arranged along two perpendicular axes, while the hexagonal cavities (25, 26, 27, 28, 29) of the transmitting filter (4) form the shape of a fragment of a five-cell honeycomb, with the fifth and ninth hexagonal cavity (25, 29) arranged in one row, and the sixth, seventh, and eighth hexagonal cavity (26, 27, 28) arranged in another row underneath, parallel thereto, where one of the side walls of the eighth hexagonal cavity (28) in the transmitting filter (4) neighbours on the side wall of the third hexagonal cavity (23) in the receiving filter (5), and another of its side walls on the side wall of the fourth hexagonal cavity (24) in the receiving filter (5), and where one of the side walls of the ninth hexagonal cavity (29) neighbours on the side wall of the fourth hexagonal cavity (24).

4. The diplexer according to Claim 3, **characterised in that** the non-conducting slots (32) between the hexagonal cavities (20) take the form of five-section broken lines of the "omega" shape and are shaped on both metallization layers (12, 13), where located on the second metallization layer (13) under each non-conducting slot in the first metallization layer (12) is a corresponding non-conducting slot in mirror reflection.

5. The diplexer according to Claim 4, **characterised in that** the inlet slot (33) of the transmitting port (2) and the inlet slot of the receiving port (3) take the form of two non-conducting lines formed on both sides of the conducting strips of the coplanar lines, where the said non-conducting lines are bent twice in the hexagonal cavity (20) at the right angle, forming the shape of a cylindrical chalice opening towards the inside of the cavity, and the inlet slots (33) of the antenna port (1) are composed of three non-conducting lines, where two of them are given the shape of broken lines starting with two non-conducting lines shaped on both sides of the conducting strip of the coplanar line, where one of the said non-conducting lines ends inside the ninth hexagonal cavity (29) of the transmitting filter (4), the second non-conducting line ends inside the fourth hexagonal cavity (24) of the receiving filter (3), and the third non-conducting line forms a broken line between the ninth hexagonal cavity (29) of the transmitting filter (4) and the fourth hexagonal cavity (24) of the receiving filter (5), and where inside these hexagonal cavities (29, 24) the inlet slots (33) take the form of a conical chalice narrowing down and opening towards the inside of the fourth hexagonal cavity (24) and the ninth hexagonal cavity (29).

6. The diplexer according to Claim 5, **characterised in that** the antenna port (1) is situated in the central part of the printed circuit board (10) and is connected with the neighbouring side walls of the fourth hexagonal cavity (24) in the receiving filter (5) and the ninth hexagonal cavity (29) in the transmitting filter (4), while the transmitting port (2) and the receiving port (3) are situated on opposite sides of the antenna port (1), where the transmitting port (2) is connected with the side wall of the fifth hexagonal cavity (25), the wall being opposite with respect to the same cavity's side wall neighbouring on the side wall of the seventh hexagonal cavity (27), and the receiving port (3) is connected with the side wall of the first hexagonal cavity (21) opposite its side wall neighbouring on the side wall of the fourth hexagonal cavity (24).

7. The diplexer according to Claim 6, **characterised in that** the transmitting port (2) and the receiving port (3) are formed on the first metallization layer (12), while the antenna port (1) is shaped on the second metallization layer (13), where the axis of the transmitting port (2) and the axis of the receiving port (3) are positioned at an angle larger than 20^0 with respect to the axis of the antenna port (1).

8. The diplexer according to any of the Claims 1-7, **characterised in that** the printed circuit board (10) features three microwave coaxial connectors (40) integrated, respectively, with the antenna port (1), transmitting port (2), and receiving port (3), and is fitted in a metal casing (50) composed of a body (51) which contacts the first metallization layer (12) and a cover (52) which contacts the second metallization layer (13), where the body (51) and the cover (52) feature shaped empty chambers (53) over the non-conducting slots (32), and separate empty chambers (53) over the inlet slots (33), they also feature connecting holes (54) and mounting holes (55).

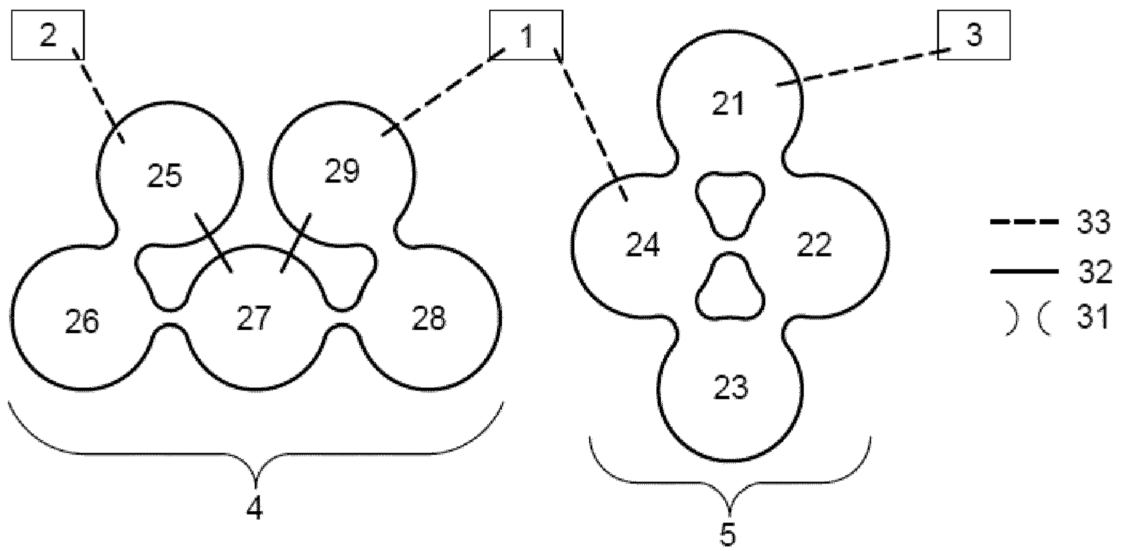
9. The diplexer according to Claim 8, **characterised in that** the coplanar lines are of minimum length required for their integration with the microwave coaxial connectors (40), and the printed circuit board (10) takes the shape of a polygon incorporating all hexagonal cavities (20) and all ports (1, 2, 3), where the minimum dimensions of the board ensure its integration with the body (51) and the cover (52).

10. The diplexer according to Claim 8, **characterised in that** the casing (50) features ventilation openings (58) and additional openings (59).

11. The diplexer according to Claims 8 - 10, **charac-**

terised in that the body (51) of the casing (50) is larger than the outline of the printed circuit board (10) and takes the shape of a square plate the side of which is 10 cm long or shorter, and the cover (52) covers only the central part of the printed circuit board (10) with the antenna port (1), non-conducting slots (32) between the hexagonal cavities (20), and the inlet slots (33) of the antenna port (1).

12. The diplexer according to any of the Claims 1- 11, **characterised in that** the dimensions of the hexagonal cavities (20), the metallized via-holes (15), windows (31), non-conducting slots (32), inlet slots (33), and coplanar lines are designed and configured so that they transmit, through the transmitting filter (4) the frequencies of the X band ranging from 8025 to 8500 MHz, and through the receiving filter (5) the frequencies of the X band ranging from 7145 to 7250 MHz, with the quality factor above 450 and insulation between the transmission channel and the reception channel above 80 dB.


2
1
3
25
29
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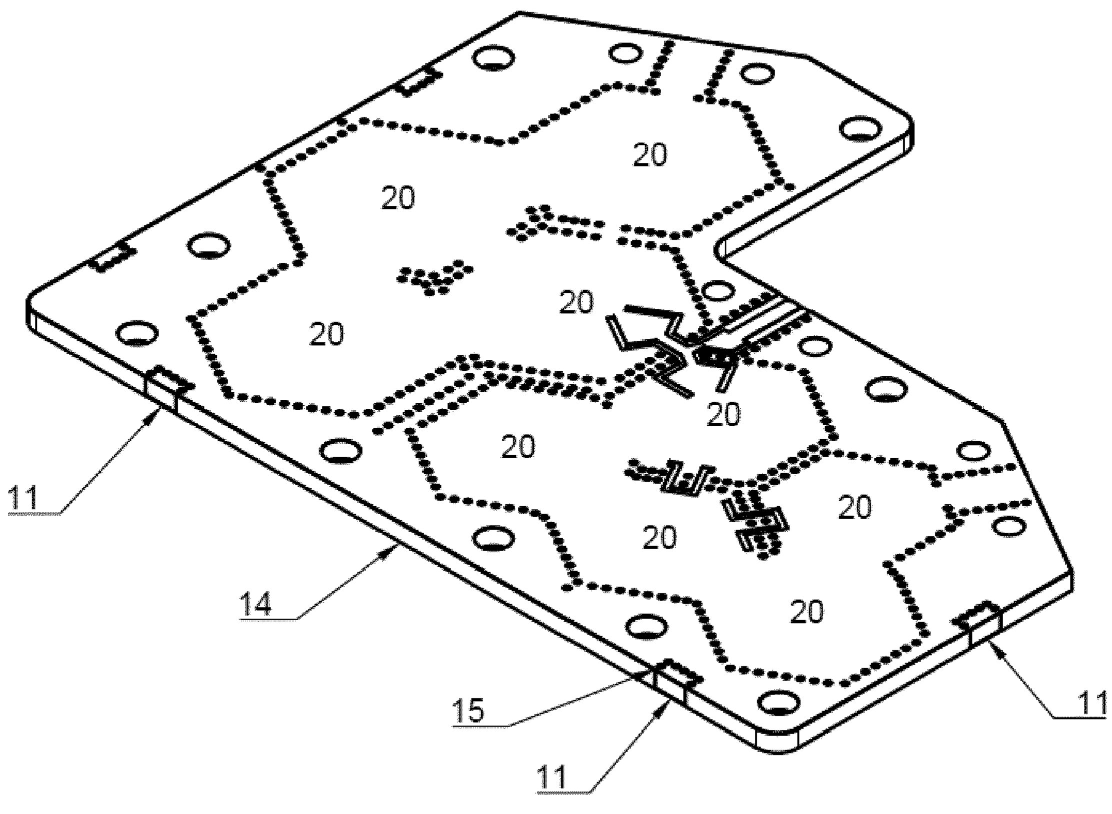
24
22
26
27
28
23
4
5
33
32
31

Fig. 1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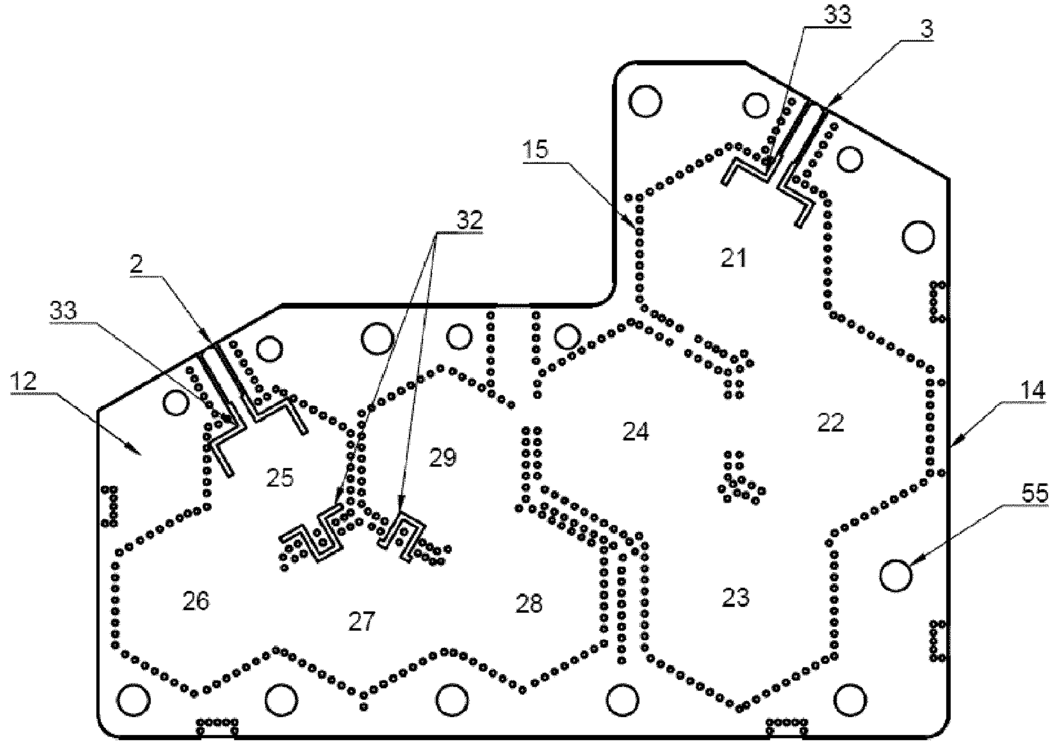
11
14
15
11
11

Fig. 2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3
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12
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22
14
25
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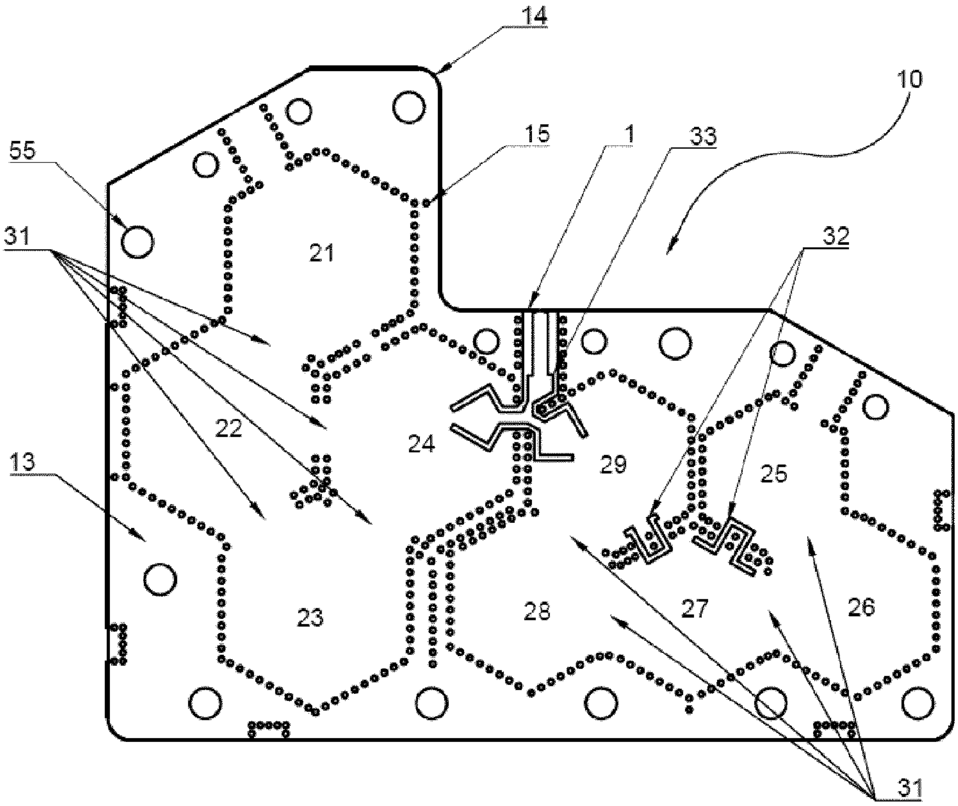
26
27
28
23

Fig. 3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32
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24
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25
13
23
28
27
26
31

Fig. 4

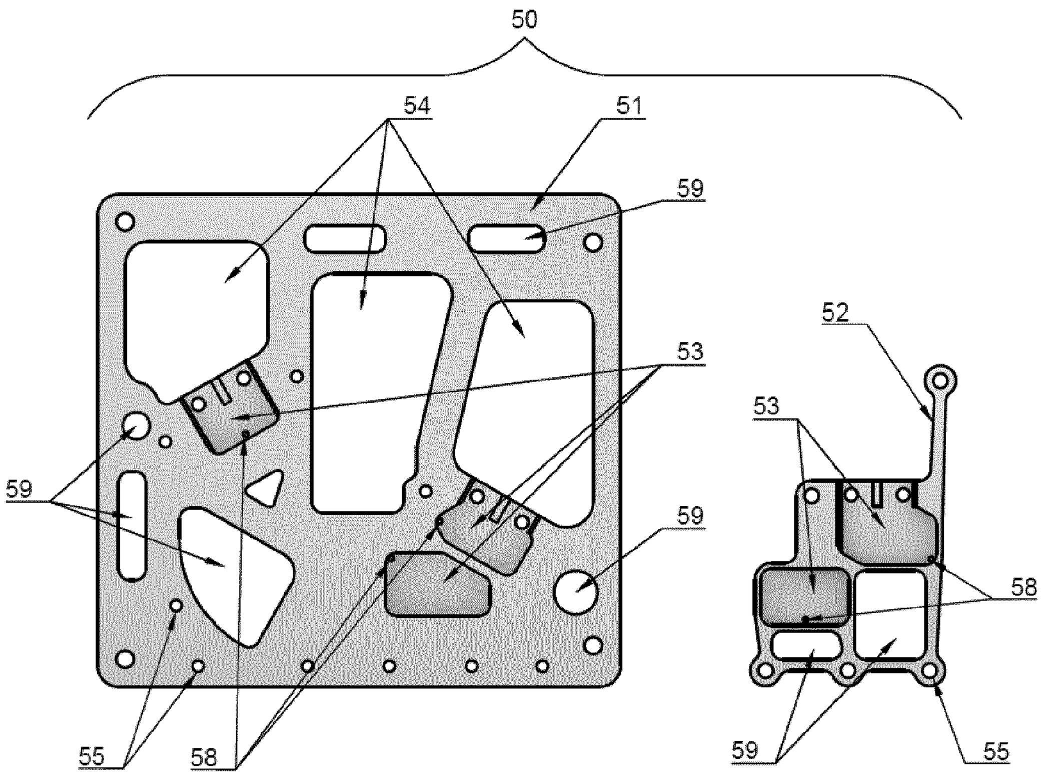


Fig. 5

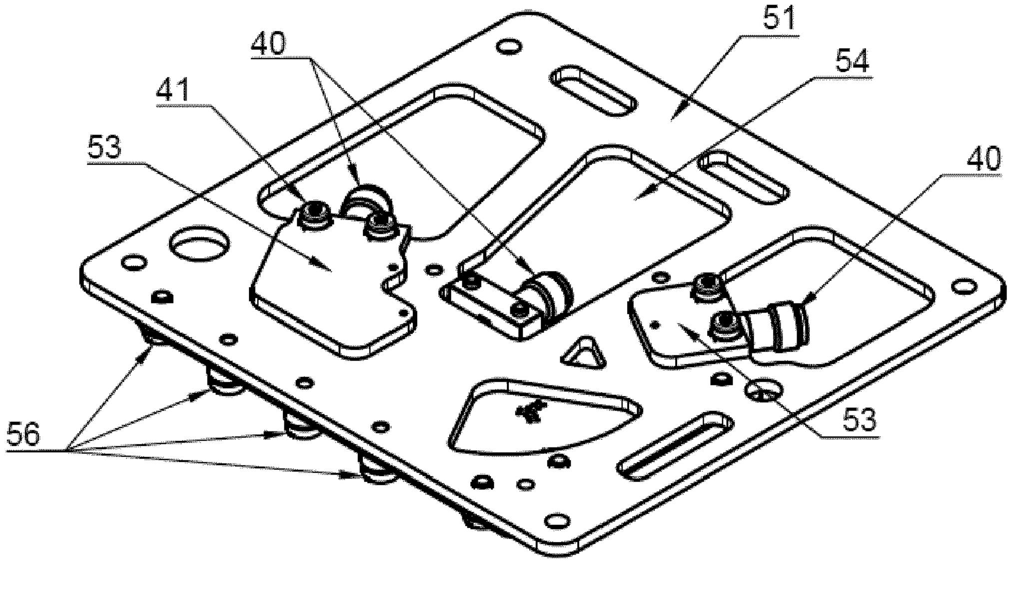


Fig. 6

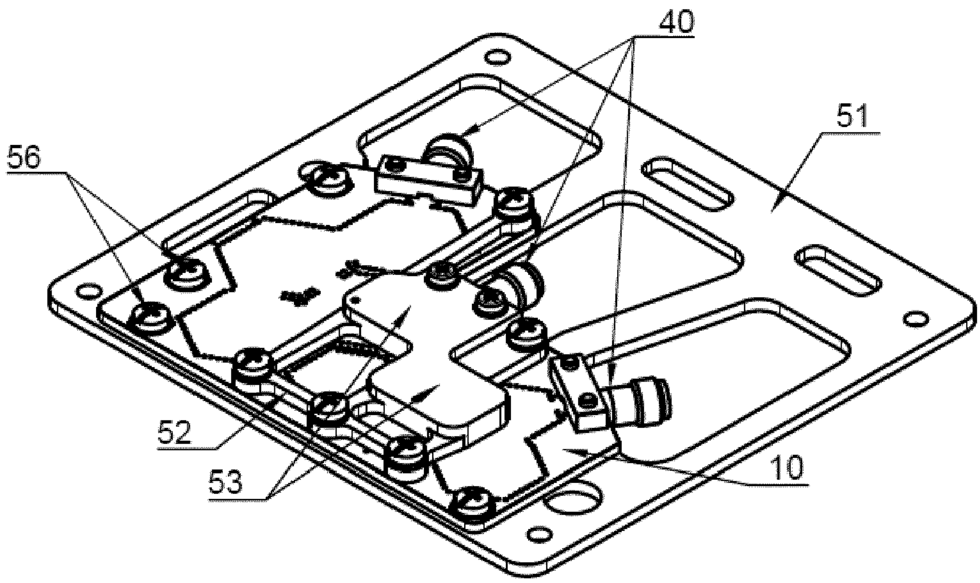


Fig. 7

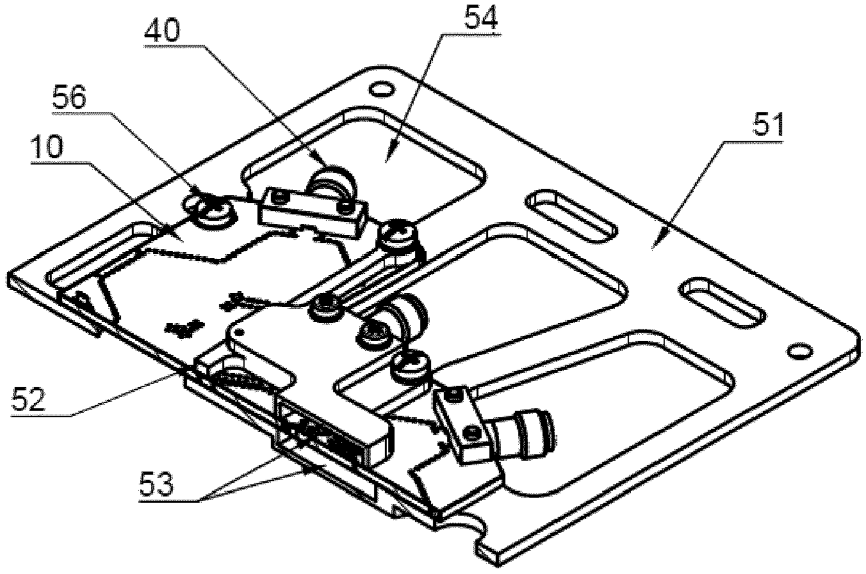


Fig. 8

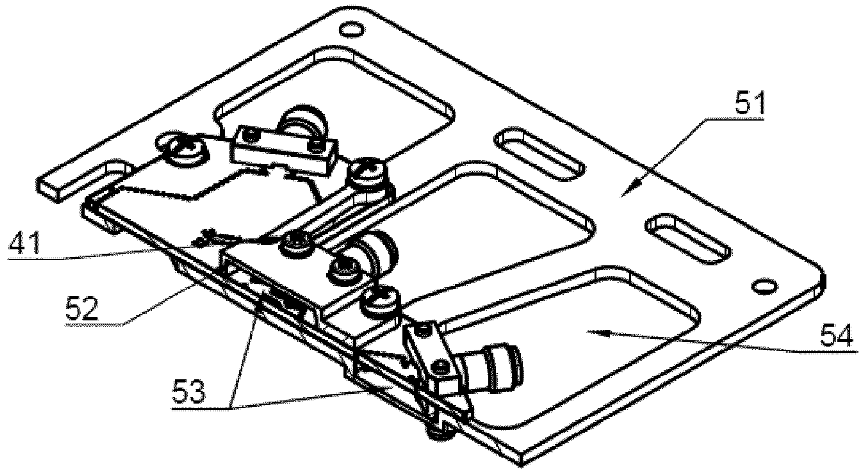


Fig. 9

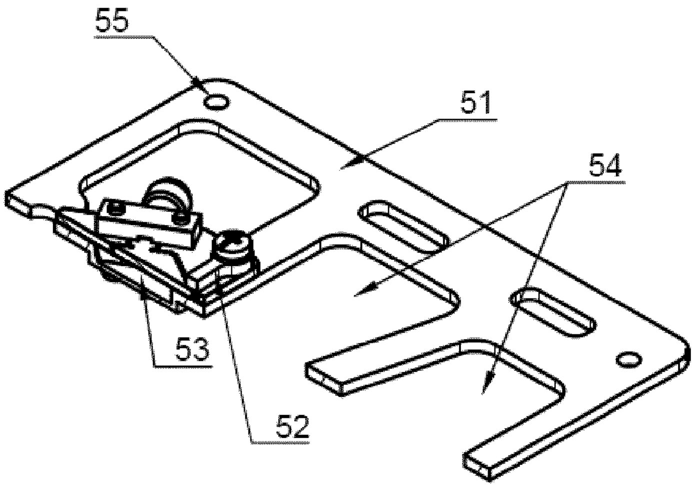


Fig. 10

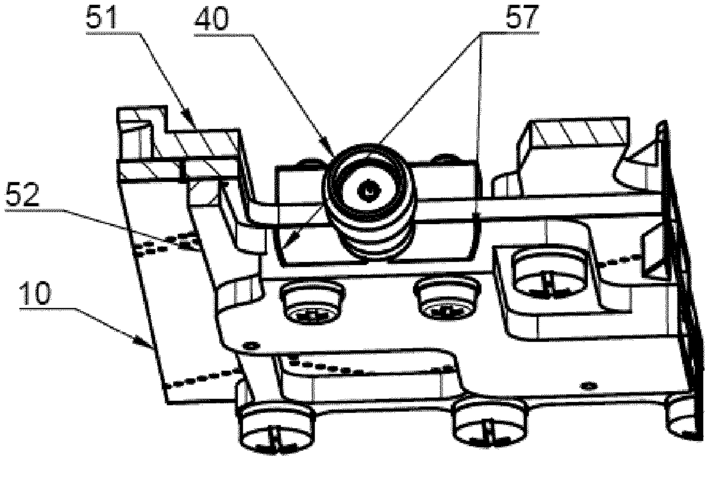


Fig. 11

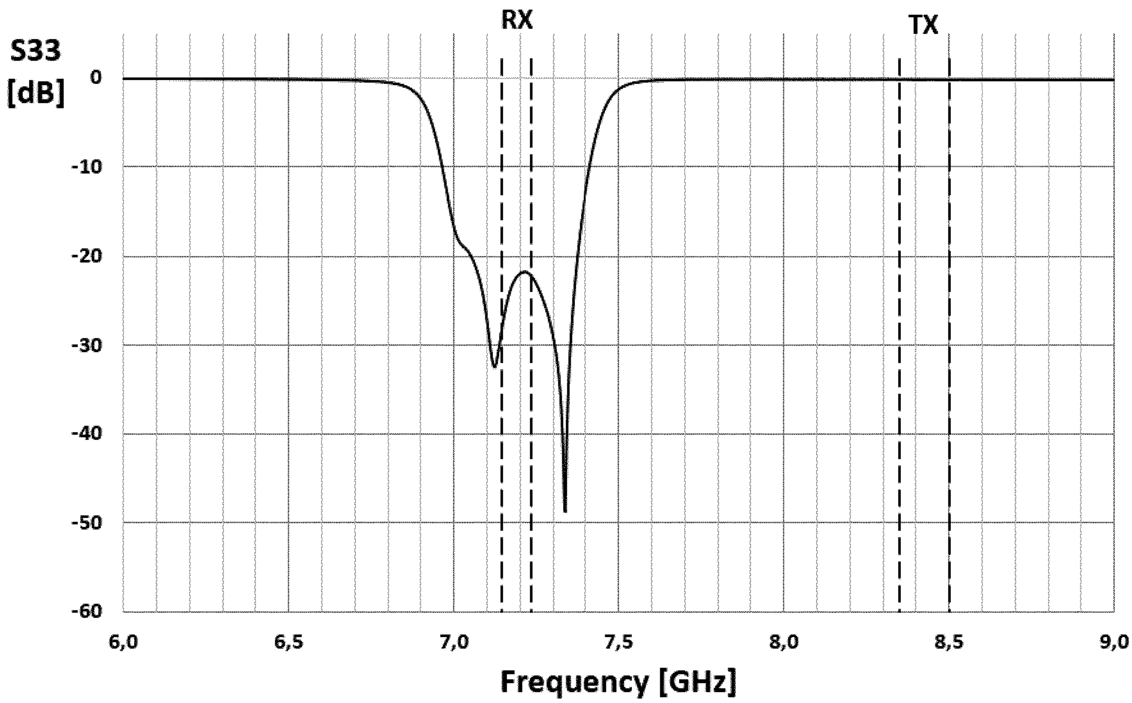

RX
TX
S33
[dB]
0
-10
-20
-30
-40
-50
-60
6,0
6,5
7,0
7,5
8,0
8,5
9,0
Frequency [GHz]

Fig. 12

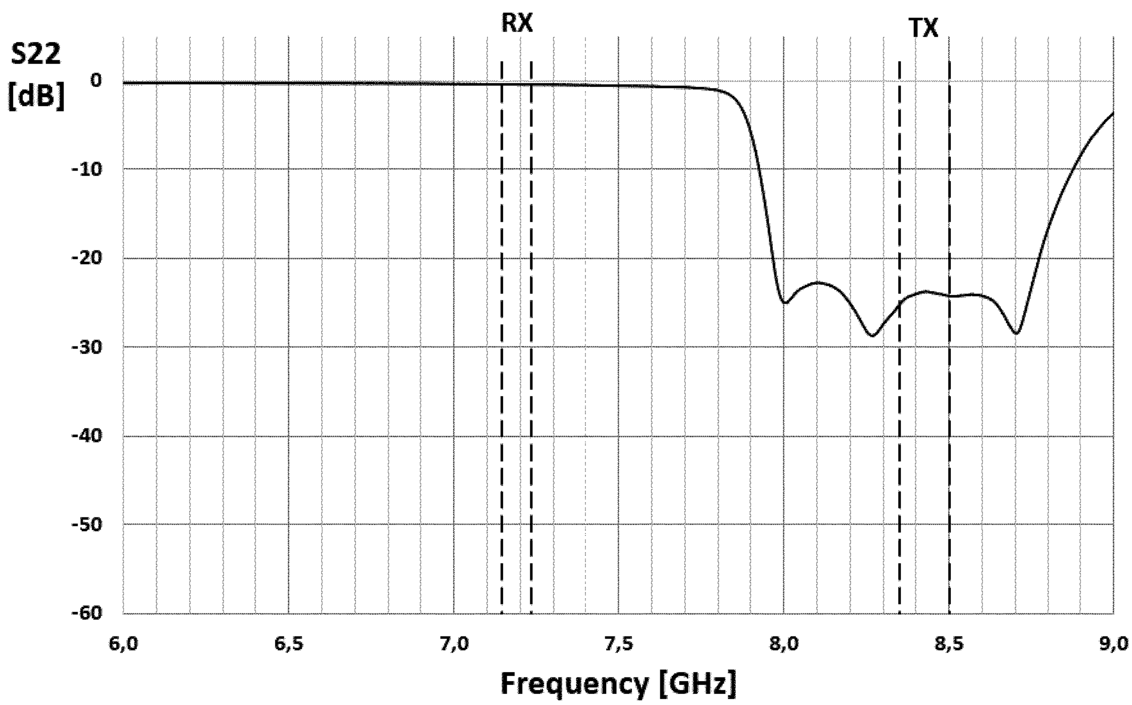
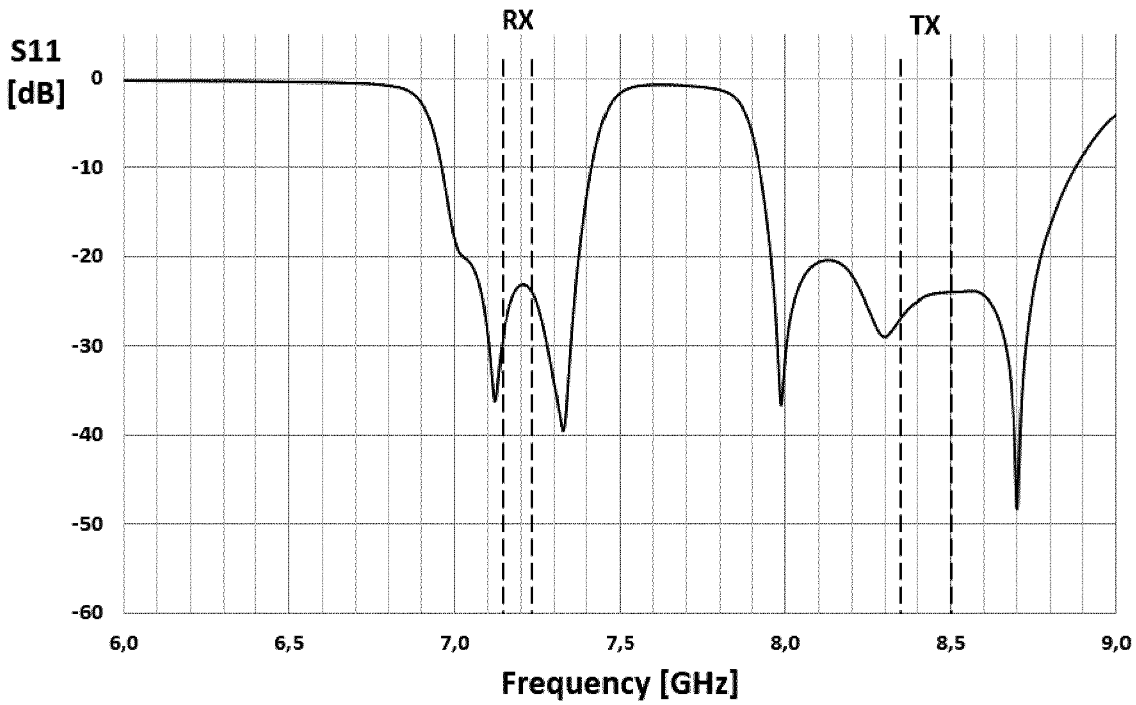

RX
TX
S22
[dB]
0
-10
-20
-30
-40
-50
-60
6,0
6,5
7,0
7,5
8,0
8,5
9,0
Frequency [GHz]

Fig. 13


RX
TX
S11
[dB]
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-10
-20
-30
-40
-50
-60
6,0
6,5
7,0
7,5
8,0
8,5
9,0
Frequency [GHz]

Fig. 14

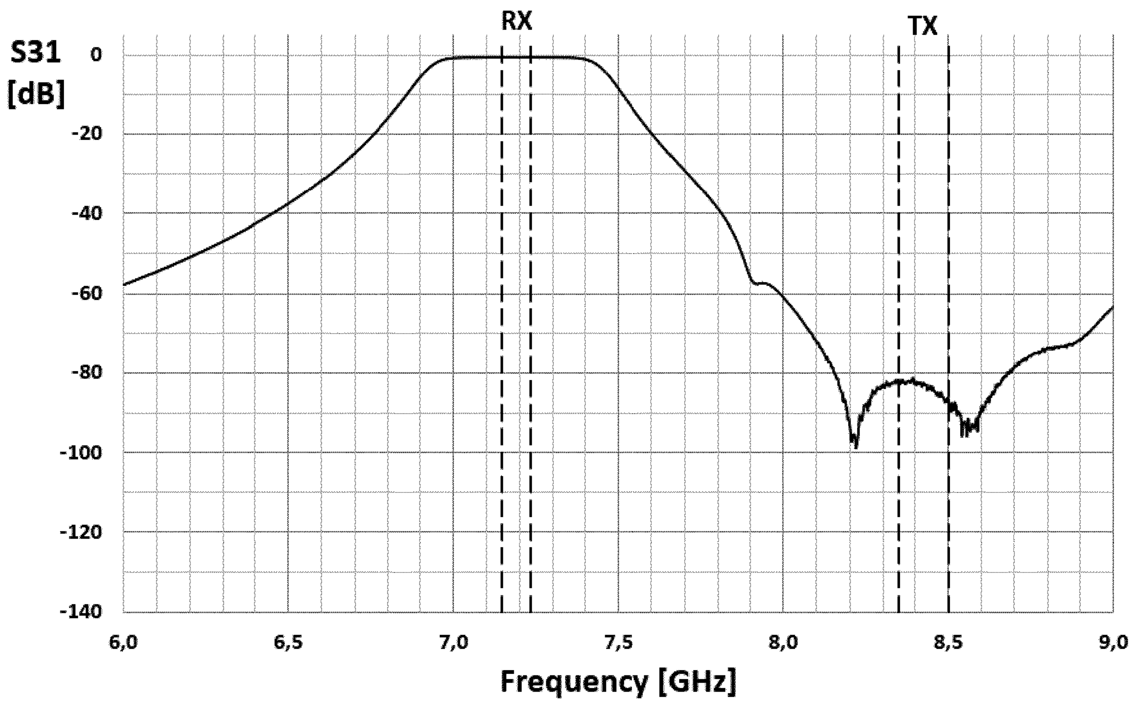
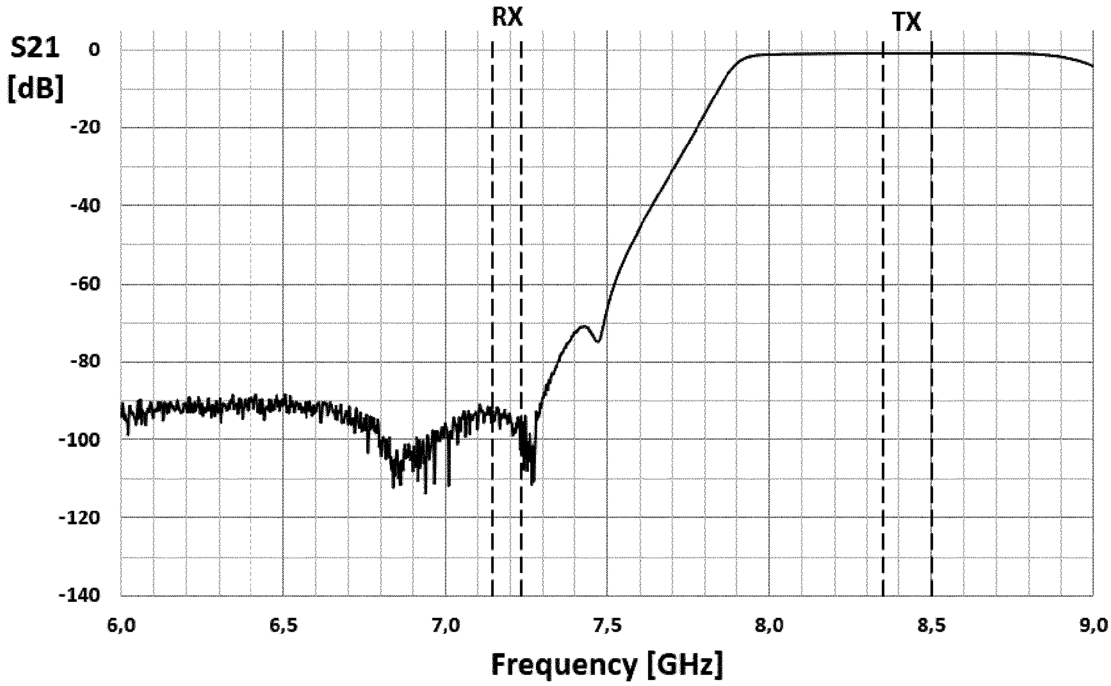

RX
TX
S31
[dB]
0
-20
-40
-60
-80
-100
-120
-140
6,0
6,5
7,0
7,5
8,0
8,5
9,0
Frequency [GHz]

Fig. 15


RX
TX
S21
[dB]
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-40
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6,0
6,5
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7,5
8,0
8,5
9,0
Frequency [GHz]

Fig. 16

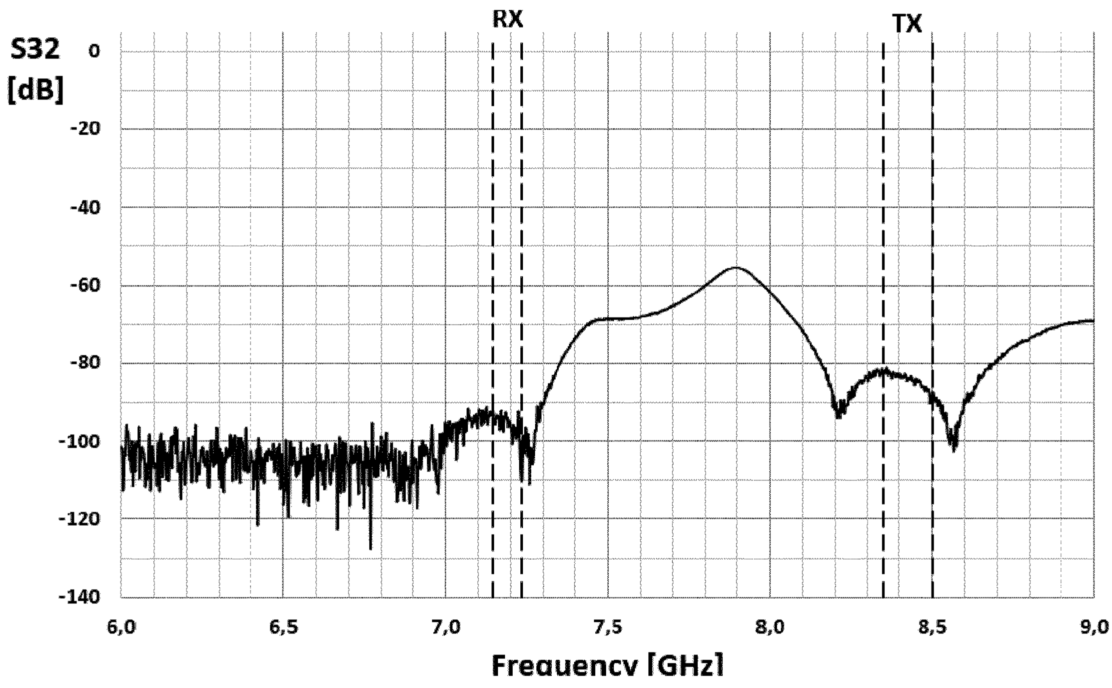
RX
TX
S32
[dB]
0
-20
-40
-60
-80
-100
-120
-140
6,0
6,5
7,0
7,5
8,0
8,5
9,0
Frequency [GHz]

Fig. 17

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EUROPEAN SEARCH REPORT

Application Number
EP 23 02 0536

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	STEFANSKI ROBERT ET AL: "High Isolation X-band and S-band Diplexers in Economical Technologies for Space Applications", 2022 24TH INTERNATIONAL MICROWAVE AND RADAR CONFERENCE (MIKON), WARSAW UNIVERSITY OF TECHNOLOGY, 12 September 2022 (2022-09-12), pages 1-6, XP034214829, [retrieved on 2022-10-25] * chapters I and IV; figures 6, 8; table 5 * -----	1-12	INV. H01P1/208 H01P1/213
X	STEFANSKI ROBERT ET AL: "Compact High Isolation SIW X-band Diplexer for CubeSat Nano-satellites", 2019 EUROPEAN MICROWAVE CONFERENCE IN CENTRAL EUROPE (EUMCE), EUMCE, 13 May 2019 (2019-05-13), pages 461-465, XP033634496, [retrieved on 2019-10-16]	1-4,8-12	
A	* chapters IV-VI; figures 3, 8, 10, 11; table 1 * -----	7	TECHNICAL FIELDS SEARCHED (IPC)
A	CHONGDER PRASUN ET AL: "Flexible design procedure for realisation of dual-mode substrate integrated hexagonal-cavity-based diplexer", IET MICROWAVES, ANTENNAS & PROPAGATION, THE INSTITUTION OF ENGINEERING AND TECHNOLOGY, UNITED KINGDOM, vol. 11, no. 14, 19 November 2017 (2017-11-19), pages 2083-2090, XP006064443, ISSN: 1751-8725, DOI: 10.1049/IET-MAP.2017.0089 * chapters II and III; figures 1, 5 * -----	1	H01P

1 The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	26 April 2024	Hueso González, J

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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- WO 2022147627 A1 **[0006]**
- KR 101514155 B1 **[0007]**
- CN 110289468 A **[0008]**