Combined L–S-bands antenna module

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Abstract: A combined L–S-band antenna module consists of four rectangular patch antennas, two of which operate at the frequencies of the first harmonics (L-band), and two others at the frequencies of the second harmonics (S-band). The module is intended for use in super heterodyne signal reception circuits, for example in studying the various non-linear phenomena. The results of this study are presented in terms of improving the performance of each antenna and minimising their mutual influence. The multi-frequency antennas can be extended to study the non-linear processes. In this way, the main problem will be to study the radiation characteristics of the antenna at higher harmonics that can arise, for example, as the result of the interaction of the electromagnetic radiation with a non-linear medium under test. In this case, the operational frequencies of the antennas should differ by a factor of two and the realisation of these conditions can be ensured by designing the antenna module comprising of at least two antennas operating on two lower harmonics of the microwave signal. To increase the sensitivity of such an antenna module, the super-heterodyne circuit of measurements seems to be most appropriate. To implement this idea, a combined system with four microstrip antennas was proposed in [9], two of which operate on the first harmonic and other two operate on the second harmonic. In this case, the frequency shift between the antennas on each of the harmonics at 50 MHz allows for using the super-heterodyne receive circuit of measurements. However, the characteristics of the antennas obtained in [9] required improvement, namely, it was first shown in Fig. 1, we also used additional 50-Ω matching microstrip lines (5, 6, 9, 10). Furthermore, as shown in Fig. 1, we also used additional 50-Ω matching microstrip lines (7, 8, 11, 12).

1 Introduction

When designing the multi-frequency microstrip antennas, the patch antennas are widely used [1–6]. In this case, the same antenna should operate at least in two frequency bands [7, 8]. This is achieved in various ways, for example by cutting the rectangular slits at the sides of the patch [1], by using the slots of different configurations to reduce the size of the antenna and to ensure a multi-frequency operation [2, 3], by inserting various elements in the patch [4] and by other ways.

As a rule, such antennas are first considered to operate at mobile communication frequencies. The main requirements for such antennas are as follows: small dimensions and weight, low profile, low cost, good matching, and high gain. However, the use of multi-frequency antennas can be extended to study the non-linear processes. In this way, the main problem will be to study the radiation characteristics of the antenna at higher harmonics that can arise, for example, as the result of the interaction of the electromagnetic radiation with a non-linear medium under test. In this case, the operational frequencies of the antennas should differ by a factor of two and the realisation of these conditions can be ensured by designing the antenna module comprising of at least two antennas operating on two lower harmonics of the microwave signal. To increase the sensitivity of such an antenna module, the super-heterodyne circuit of measurements seems to be most appropriate. To implement this idea, a combined system with four microstrip antennas was proposed in [9], two of which operate on the first harmonic and other two operate on the second harmonic. In this case, the frequency shift between the antennas on each of the harmonics at 50 MHz allows for using the super-heterodyne signal receiving. However, the characteristics of the antennas obtained in [9] required improvement, namely, it was first shown in Fig. 1, we also used additional 50-Ω matching microstrip lines (5, 6, 9, 10). Furthermore, as shown in Fig. 1, we also used additional 50-Ω matching microstrip lines (7, 8, 11, 12).

2 Antenna design

The radiation of antennas at the first and second harmonics assumes that they operate in two adjacent frequency bands. The antenna module proposed consists of four rectangular patch antennas 1–4 (Fig. 1), two of which (1, 3) operate at the frequencies of the first harmonics (L-band), and the remaining two (2, 4) at the frequencies of the second harmonics (S-band), respectively. The resonance frequencies of the L- and S-bands antenna differ by 50 MHz.

To realise the aforementioned goal, we have chosen the microstrip rectangular patch antennas with diagonal symmetry, which have low profile, low cost, and simple fabrication. All the patch antennas were manufactured by photolithography. The antennas are implemented on a ROGERS R03210 substrate with the relative permittivity of $\varepsilon_r = 10.2$, tan $\delta = 0.0027$, and the substrate thickness of $h = 1.27$ mm. Herewith, a coppering thickness of the metallic patch is $t = 0.035$ mm.

The excitation of the antennas is realised by means of the 50-Ω impedance microstrip feeding lines (5, 6, 9, 10). Furthermore, as shown in Fig. 1, we also used additional 50-Ω matching microstrip lines (7, 8, 11, 12).
As a result of the simulations, the optimal geometric parameters of the antennas for their operation at the fixed frequencies; (ii) to provide the isolation between the antennas at the specified frequency bands, a numerical analysis was carried out by the program packet ANSYS HFSS. The main problems of the numerical modelling were as follows: (i) to find the optimal geometrical parameters of the antennas for achieving the desired operation in the respective frequency bands, they are 3.68 GHz (antenna 2) and 3.78 GHz (antenna 4), respectively. The bandwidths of the antennas operating on the first harmonics are $\Delta f_1 = 10 \pm 1\,\text{MHz}$, and of the antennas operating on the second harmonics they are $\Delta f_2 = 50 \pm 1\,\text{MHz}$.

Following the results of the simulations, the antenna module has been manufactured and tested (Fig. 3). As an example, the calculated and measured reflection coefficients ($S_{11}$) of the antennas 1 and 2 have shown in Fig. 4. As can be seen, the measured and simulated resonance frequencies are in excellent agreement ($f_1 = 1.84\,\text{GHz}$ for the antenna 1 and $f_2 = 3.68\,\text{GHz}$ for the antenna 2). For the other two antennas (antennas 3 and 4), the measured and calculated $S_{11}$ values are in good agreement too. The resonance frequencies are $f_3 = 1.89\,\text{GHz}$ for the antenna 3 and $f_4 = 3.78\,\text{GHz}$ for the antenna 4, respectively. Herewith, the bandwidths of the receiving antennas (antennas 2 and 4) have been reduced by half in comparison with the results given in [9].

The radiation patterns of antennas 1 and 2 in two principal planes are shown in Fig. 5. Notice that the calculated and measured elevation angles of the peak directivity $\Theta_{\text{max}}$ are close to the zenith for all the antennas (see Table 2). Herewith, the measured radiation patterns are narrower than the calculated ones and their beamwidths are in the interval of the angles $64^\circ \leq \Delta \Theta \leq 68^\circ$. So, the beamwidths of all the antennas are virtually the same in both the principal planes and it is especially important that in contrast to the results in [9] the level of the side lobes does not exceed $-20\,\text{dB}$.

To analyse the effect of the radiation field of each of the antennas on another one, near-field measurements were carried out using the procedure described in [10]. Since the results of the near-field measurements of any two adjacent antennas have practically repeated, we confine ourselves to a representation of the field pictures of two antennas, in particular, of antennas 1 and 2. Fig. 6 shows the near-fields measured in the inductive region by a magnetic dipole at the successive excitation of each of the antennas. In the first case, the antenna 1 is excited through the 50-Ω impedance microstrip feeding line 5, and the 50-Ω load is attached to the feeding line 6 of the antenna 2. As one can see from the field pictures, the field power of the magnetic component is concentrated in the area of the patch side nearest to the antenna 2 (Fig. 6a). It is worth noting that, in this case, there is some background radiation that covers almost the entire analysed space above the antenna. The intensity of this radiation is of the order of $-9\,\text{dBi}$ relative to the maximum intensity level over the patch of the antenna 1. In the second case, the antenna 2 is excited through the 50-Ω impedance microstrip feeding line 6, and the 50-Ω load is attached to the feeding line 5. The antenna 1 remains insensitive to the constituent elements of each of the antennas were determined (see Table 1). The reflection coefficient $S_{11}$ of the antennas is shown in Fig. 2. The reflection coefficients of the L-band antennas are 1.84 GHz (antenna 1) and 1.89 GHz (antenna 3) and of the S-band antennas, they are 3.68 GHz (antenna 2) and 3.78 GHz (antenna 4), respectively. The bandwidths of the antennas operating on the first harmonics are $\Delta f_1 = 10 \pm 1\,\text{MHz}$, and of the antennas operating on the second harmonics they are $\Delta f_2 = 50 \pm 1\,\text{MHz}$.

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| Geometry of the antenna module | | | | |
|-----------------|-----------------|-----------------|-----------------|
| Fig. 1 Geometry of the antenna module |

| Table 1 Geometrical parameters of antennas |
|------------------------------------------|
| Parameter | Antenna 1 | Antenna 2 | Antenna 3 | Antenna 4 |
| dx, mm    | 29.6      | 12.5      | 29.4      | 11.9      |
| dy, mm    | 26.7      | 11        | 26.1      | 12.5      |
| du, mm    | 4.4       | 5.7       | 4         | 3.6       |

| Fig. 2 Simulated parameter $S_{11}$ for all the antennas |
|----------------------------------------------------------|

| Fig. 3 Prototype of the antenna module |
|---------------------------------------|

3 Results and discussion

To determine the appropriate geometrical parameters of the antennas for achieving the desired operation in the respective frequency bands, a numerical analysis was carried out by the program packet ANSYS HFSS. The main problems of the numerical modelling were as follows: (i) to find the optimal configurations of the antennas for their operation at the fixed frequencies; (ii) to provide the isolation between the antennas at the specified frequency bands, they are 3.68 GHz (antenna 2) and 3.78 GHz (antenna 4), respectively. The bandwidths of the antennas operating on the first harmonics are $\Delta f_1 = 10 \pm 1\,\text{MHz}$, and of the antennas operating on the second harmonics they are $\Delta f_2 = 50 \pm 1\,\text{MHz}$.

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the radiation of the antenna 2 that follows from the absence of the microwave power on its aperture (Fig. 6b).

The results obtained indicate a need to take the relevant actions to eliminate this undesirable effect. This can be achieved by inserting a gap between the antennas.

In Fig. 7, the measured frequency dependence of the transmission coefficient $S_{12}$ for different widths $DX$ of the gap is given. In this case, the input signal excites the antenna 1 and the output signal is received by the antenna 2. Note the presence of resonances between the frequencies of the first and second harmonics, i.e. at $f=2.33$, 2.86, and 3.2 GHz. These resonance regions can be a consequence of additional matching of two electrodynamically matched antennas just at these frequencies, although there is a gap between the antennas. This explanation is corroborated by the fact that this effect decreases when the gap increases. Based on the dependencies obtained, one may conclude that the transmission coefficient $S_{12}$ decreases with the increase in the gap $DX$ between the antennas and for $DX>13$ mm the parameter $S_{12}$ becomes $<-50$ dB that is already an acceptable value from the point of view of implementing the aforementioned goal.

The measurements of the near fields of the antennas were carried out for various gaps $DX$ while both the antennas 1 and 2 were excited simultaneously at their respective resonance frequencies. When the distance between the antennas $DX=0$, there is a strong electromagnetic coupling between the antennas (Fig. 8a) that corresponds to the value $S_{12}=-25$ dB (see Fig. 7). The increase in the distance between the antennas leads to the decrease

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![Fig. 4 Reflection coefficients $S_{11}$ of
(a) Antenna 1
(b) Antenna 2](image)

![Fig. 5 Calculated and measured radiation patterns in two principal planes of
(a) Antenna 1
(b) Antenna 2](image)

| Table 2 | Parameters of antennas |
|---------|------------------------|
| Experiment | ZOY-plane | ZOX-plane |
| | $\Theta_{\text{max}}$ | $\Delta \Theta$ | $\Theta_{\text{max}}$ | $\Delta \Theta$ |
| Antenna 1 | 91° | 64° | 89° | 65° |
| Antenna 2 | 91° | 65° | 88° | 64° |
| Antenna 3 | 92° | 66° | 94° | 67° |
| Antenna 4 | 91° | 68° | 91° | 65° |

| Simulation | ZOY-plane | ZOX-plane |
|-----------|----------|----------|
| | $\Theta_{\text{max}}$ | $\Delta \Theta$ | $\Theta_{\text{max}}$ | $\Delta \Theta$ |
| Antenna 1 | 89° | 162° | 82° | 141° |
| Antenna 2 | 89° | 88° | 84° | 102° |
| Antenna 3 | 93° | 119° | 91° | 119° |
| Antenna 4 | 91° | 98° | 92° | 88° |
in the electromagnetic field in the gap and already at $DX = 13$ mm the radiation level drops tangibly (Fig. 8b). In this case, the transition coefficient $S_{12}$ does not exceed $-50$ dB (see Fig. 7).

Such studies (both calculations and measurements) were carried out by the authors. It was found that for distances $DX > 10$ mm the parameter $S_{12}$ in the operational frequency band for each of the antennas is of the order of $-50$ dB. At the same time, the analysis of the measured spatial distributions of the near fields while changing the distance $DX$ with a 2 mm discrete from $DX = 0$ mm to $DX = 16$ mm has shown that at the distances $DX \geq 13$ mm the near-field distribution above both the antennas does not change. In Fig. 7, two-field distributions with the maximum mutual influence of the antennas ($DX = 0$ mm) and at a distance from which this influence can be neglected ($DX = 13$ mm) have been shown. Therefore, the distance $DX = 13$ mm can be considered as an optimal one, both from the point of view of the minimum value of $S_{12}$, and from the point of view of near-field distributions of the antennas.

4 Conclusions

As a result of the investigations carried out in the work of each of the antennas included in the module, their optimum dimensions were determined for operation at the following resonance frequencies: 1.84 and 1.89 GHz for the L-band antennas, 3.68 and 3.78 GHz for the S-band antennas, respectively. The reflection coefficients are as follows: $S_{11} < -30$ dB for the transmitting antenna, and $S_{11} < -20$ dB for the receiving antenna, herewith the bandwidths of the receiving antennas have been reduced by half in comparison with the results given in [9]. Measured radiation patterns in the H- and E-planes are practically identical with the elevation angle of the peak directivity close to the zenith. For high sensitivity of the measurements at the second harmonic, the minimal distance $DX = 13$ mm between the antennas has been determined to provide the electromagnetic isolation $<-50$ dB.

The module proposed seems to be very significant for different telecommunication applications as well as for studying various non-linear phenomena.
Experimental studies of the manufactured module in the transceiver mode using the super-heterodyne circuit of signal receiving are in progress.

5 References

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