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Spurious and Intermodulation Response Analysis of Passive Double-Balanced Mixers using the Double-Frequency Scanning Technique

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***Abstract* — The application of the automated double-frequency test technique (ADFTT) to the analysis of mixer-generated nonlinear products is described. The distinctive feature of this technique is the ability to detect all nonlinear effects appearing in the device under test. Using the ADFTT, the detailed experimental analysis of three modern double-balanced mixers is performed, which includes the detection, recognition, and characterization of the mixer interference responses. As a result of the analysis, it is found a high susceptibility of the mixers to such types of spurious-response and intermodulation interference that are not traditionally considered as the most dangerous. This peculiarity must be taken into account when solving EMC problems of co-site radio systems.**

Keywords* — *balanced mixer, nonlinear interference, receiver, intermodulation, spurious response

I. INTRODUCTION

Electromagnetic compatibility of radio communication and radio navigation equipment, radars, and other radio systems of different services located in the limited-space onboard (aircraft, ship, car, etc.) and local land (airport, seaport, radio communication centre, etc.) objects is substantially determined by spurious and intermodulation responses of radio receivers involved in these systems. It is also determined by possibilities of application of spectrum management and frequency planning technique for solving electromagnetic compatibility (EMC) problems when the levels of receiver input signals exceed its susceptibility threshold for intermodulation and approach its susceptibility threshold for desensitization.

In turn, the structure and characteristics of the receiver's spurious and intermodulation responses depend on types and characteristics of the receiver's input elements, in particular, on properties of an input mixer. Passive diode mixers, in particular, double-balanced mixers (DBMs) are widely used in low- and medium-cost microwave receivers. The main advantages of a DBM are smaller "density" of higher harmonics and combination frequencies of input signals in the output spectrum, wider dynamic range of input signals and higher input power, broadbandness, good isolation between all ports (RF input port, LO input port, and IF output port), and moderate noise factor [1, 2, 3].

Less known DBM properties, which cause certain difficulties in EMC development for a receiver having the DBM at the input, are the following.

- The extremely sharp increase in number of low-order spurious and intermodulation responses involving the higher harmonics of the local oscillator (LO) signal when the level of input signal exceeds the intermodulation susceptibility of the DBM [4]. This phenomenon limits the application of spectrum management and frequency planning technique for solving the EMC problems of co-site radio systems.
- The impossibility of adequate behavior simulation of these devices under the powerful stimulus at the radio frequency (RF) input [3], which is a serious obstacle to achieving the required objectivity in definition of EMC characteristics for a receiver with front-end DBM by computer analysis.
- High laboriousness of detailed experimental analysis of characteristics of mixers using traditional methods [5]. This makes it difficult to obtain the necessary volume of information on physical properties of mixers for the detailed EMC analysis and estimation of the possibility to achieve EMC by frequency planning technique.

In spite of a lot of works concerned to the research of some special characteristics of various-kind mixers, the aforesaid circumstances indicate the importance of in-depth study of the DBMs by new methods, including experimental investigations, in order to reveal all the features characterizing their operation as the receiver's front-end devices under the influence of powerful out-of-band input signals.

The objective of this paper is to perform the detailed experimental analysis of spurious and intermodulation products generated in modern double-balanced mixers by the instrumentality of the automated double-frequency test technique (ADFTT) and system (ADFTS) [4, 6].

The paper is organized as follows. The main idea of mixer testing with the use of ADFTS is considered in Section II, the measurement results for DBMs of different types are given in Section III, and a summary is provided in Conclusion.

II. APPLICATION OF ADFTT TO TESTING OF MIXERS

The structure of ADFTS for mixer's testing is given in Fig. 1. Real-time dependences of frequencies of ADFTS test signals generated by RF Generators 1 & 2 are illustrated by Fig. 2. LO is simulated by RF Generator 3. Low-pass filter (LPF) at the Spectrum analyzer's (SA) input provides the linear mode of its operation. SA simulates the active filter of intermediate frequency (IF) f_{IF} with bandwidth $\{F_{IFmin}, F_{IFmax}\}$. Necessary sensitivity and additional selectivity at IF may be provided with additional Selective Low-Noise Amplifier (SLNA) or high-quality measuring receiver. Actually, LO-MUT-LPF-(SLNA-)SA structure can be considered as a model of the receiver with MUT at its input. LO frequency f_{LO} of this model is determined by the tuning frequency, the intermediate frequency, and the type of LO tuning (upper / lower).

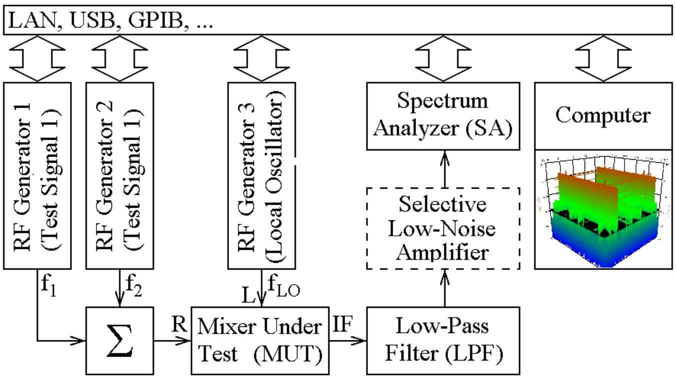

Fig. 1. Basic ADFTS structure for testing of a mixer

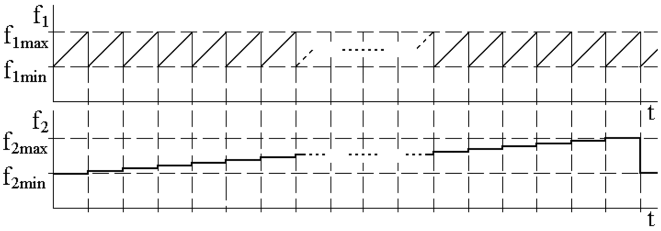

Fig. 2. Frequency sweeping in ADFTS: f_1 – frequency of a fast-sweeping test signal, f_2 – frequency of a slow-sweeping test signal

Main results of a base stage of mixer testing with the use of the ADFTT are 3D and 2D images of MUT characteristics:

- 3D image of a double-frequency characteristic (DFC) is a three-dimensional dependence of a level of the MUT output response falling into SA passband on the frequencies of two sweeping test signals of constant levels (Fig. 3),
- family of 2D images of the DFC's horizontal cross-sections: each 2D image called as a double-frequency diagram (DFD) is a color map of 3D DFC image for a given threshold (minimum level of display) of MUT output signal (Fig. 4).

Mathematically, the DFC of MUT is defined as follows:

$$H(f_1, f_2) = P_{out}(f_1, f_2 \mid P_{1in} = \text{const}, P_{2in} = \text{const}), \qquad (1)$$

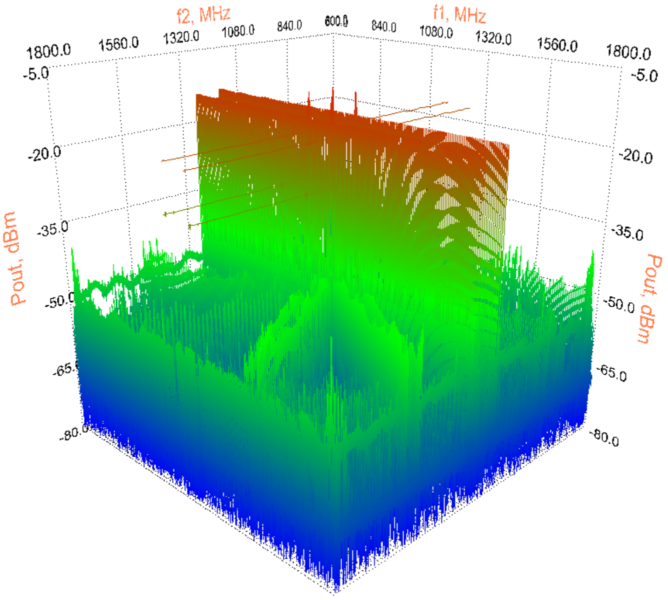

Fig. 3. 3D image of DFC: both test signals have equal levels of -10 dBm and frequency sweep ranges of 0.6 – 1.8 GHz, f_{LO} = 1.2 GHz, f_{IF} = 50 MHz.

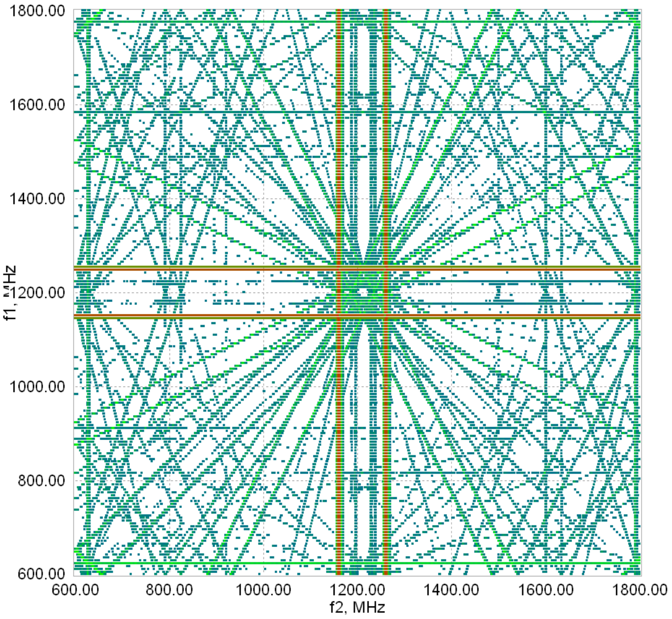

Fig. 4. 2D image (DFD) of the DFC given in Fig. 3. The display threshold is of -64 dBm, which is 6 dB above the SA noise level. The SA is tuned to f_{IF} = 50 MHz and has the bandwidth of 4 MHz.

where P_{out} is the level of the MUT output signal at the intermediate frequency observed if two test signals at frequencies f_1 and f_2 with levels P_{1in} and P_{2in} are applied to the MUT RF input.

For the DFC (1), the family of two-level (i.e., black-and-white) DFDs is defined as

$$W_i(f_1, f_2 \mid P_{ti}) = \operatorname{sgn}\{H(f_1, f_2) - P_{ti}\}, \qquad i = 1, 2, \dots, \qquad (2)$$

where i is a serial number of the DFD, sgn denotes the signum function, and P_{ti} is the i-th display threshold level. The levels

P_{ti} are selected so that they exceed the level of the MUT internal noise at its output in frequency band $[F_{IFmin}, F_{IFmax}]$.

III. RESULTS OF ADFTS-ASSISTED DBM TESTS

Frequency scanning ADFTT is applied to testing of several widespread high-quality medium-cost broadband DBMs, the types and parameters of which are given in Table I, and the electrical scheme is shown in Fig. 5 [7].

TABLE I. PARAMETERS OF MIXERS UNDER TEST (MUTS)

No.	Mixer Type	Frequency of Input RF Signal, MHz	LO Power, dBm	IF, MHz	Conv. loss, dB typ.	Approx. price, $
I	ZEM-4300+	300 - 4300	+7	0 - 1000	6.65	80
II	ZFM-11-S+	1 - 2000	+7	5 - 600	7.03	95
III	ZFM-5X-S+	1 - 1500	+7	1 - 1000	5.9	65

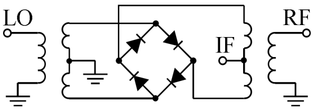

Fig. 5. Electrical scheme of DBMs I and II.

DFC and DFD given in Figs. 3 and 4 are obtained for DBM ZEM-4300+. Two pairs of fat horizontal and vertical lines in DFD (Fig. 4), symmetric with respect to the DFD's diagonal $f_1 = f_2$, belong to the desired (1150 MHz) and image (1250 MHz) responses, respectively (for upper LO tuning). Each other pair of symmetric vertical and horizontal lines is an image of corresponding spurious response, pairs of inclined lines with diagonal symmetry are images of corresponding intermodulation responses. The general equation describing the position of these lines in a double-frequency plane $\{f_1, f_2\}$ is

$$z_1 \cdot f_1 + z_2 \cdot f_2 + z_3 \cdot f_{LO} = f_{IF}, \qquad (3)$$

where z_1, z_2, z_3 are integer coefficients; f_1, f_2 are frequencies of the test signals at the MUT RF input, f_{LO} is the local oscillator (LO) frequency, f_{IF} is the intermediate frequency (IF).

The central part of the DFD given in Fig. 4 (rounding the point $f_1 = f_2 = f_{LO}$ and covering the images of the desired and image responses) is of the main interest. The magnified image of this DFD part obtained for 8 times reduced frequency sweeping bands of the test signals is resulted in Fig. 6. This DFD image have the specific central symmetry, typical for DFD of a DBM [4]. If $f_{IF} << f_{LO}$ and the frequency sweeping bandwidths of the test signals are in the range $(2…4)f_{IF}$, then the image of this DFD fragment of DBM in practice does not depend on f_{IF}.

As a result of the detailed analysis of the MUTs' DFCs obtained in the same conditions (for identical levels and frequency sweeping bands of the test signals, at the same display threshold level, and for the same SA tuning frequency and span), a number of regularities and features important for EMC of radio systems are found. These DFCs and DFDs vary for different DBM types, but all of them have the following features.

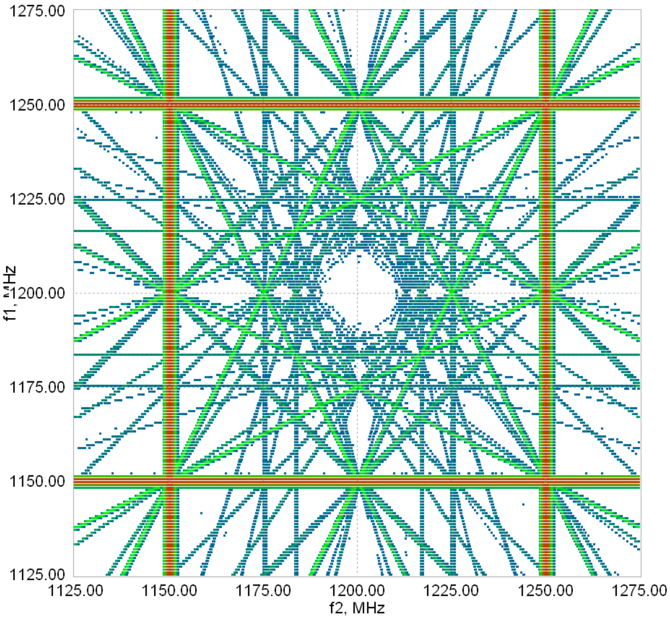

Fig. 6. DFD of mixer ZEM-4300+ as a detailed view of the central part of the DFD given in Fig. 4. Display threshold is -70 dBm, which is 6 dB above the SA noise level. The SA tuning frequency is 50 MHz, and its bandwidth is 1 MHz. The test signals have equal levels of $P_{1in} = P_{2in} = -10$ dBm and frequency sweep ranges from 1.125 GHz to 1.275 GHz.

DFDs obtained at test signal levels above the MUT susceptibility to intermodulation include a number of spurious and intermodulation responses of orders 2…5 with anomalously high susceptibility. For illustration of this conclusion, let us appeal to Figs. 7, 8, 9 in which the DFDs obtained for step-by-step 4 dB decreasing of the test signal levels are shown. In particular,

1) The DBM susceptibility to the third-order intermodulation of a "traditional" kind $2f_{1,2} - f_{2,1} = f_{LO} \pm f_{IF}$ (involving the first harmonic of the LO signal and falling into the frequency band of the desired or image response) is proved to be equal to the DBM susceptibility to a third-order intermodulation of the kind $2f_{1,2} + f_{2,1} = 3f_{LO} \pm f_{IF}$ (involving the third harmonic of the LO signal and falling into the frequency bands of spurious responses created by this LO harmonic) – ref. Figs. 8, 9, and Table II;

2) The DBM susceptibility to the second-order intermodulation of a "traditional" kind $|f_{1,2} - f_{2,1}| = f_{IF}$ (involving the direct mutual conversion of the test signal frequencies to the IF) is proved to be equal to the DBM susceptibility to a second-order intermodulation of the kind $f_{1,2} + f_{2,1} = 2f_{LO} \pm f_{IF}$ (involving the second harmonic of the LO signal and falling into the frequency bands of spurious responses, created by this harmonic) – ref. Figs. 8, 9, and Table II;

3) The similar equality of the susceptibilities to intermodulation of the fifth-order is detected for the "differential" intermodulation $3f_{1,2} - 2f_{2,1} = f_{LO} \pm f_{IF}$ and the "summary" intermodulation $3f_{1,2} + 2f_{2,1} = 5f_{LO} \pm f_{IF}$ (ref. Table III);

4) The similar situation is detected for susceptibility to intermodulation products of 2-7 orders, which are created by

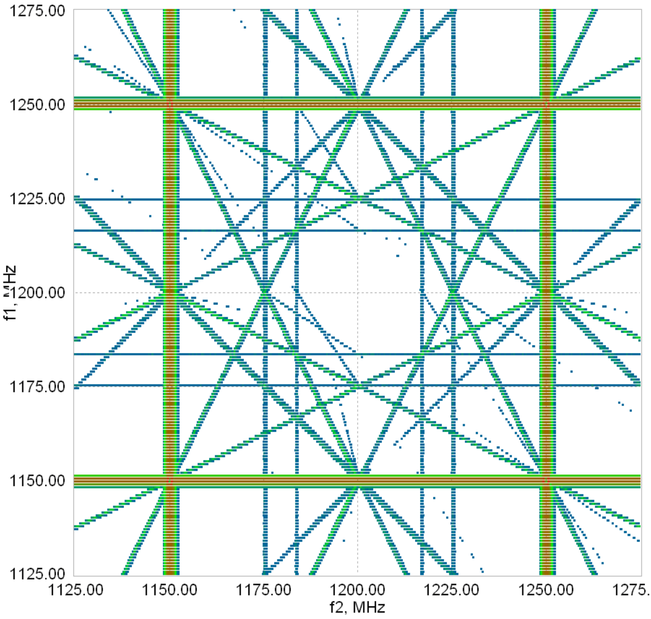

Fig. 7. DFD of mixer ZEM-4300+. The test signal levels are -14 dBm, other conditions are the same as in Fig. 6.

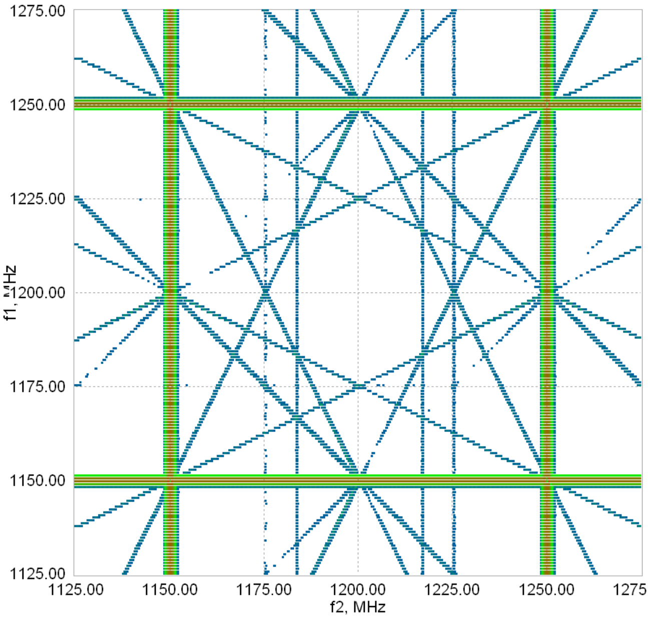

Fig. 8. DFD of mixer ZEM-4300+. The test signal levels are -18 dBm, other conditions are the same as in Fig. 6.

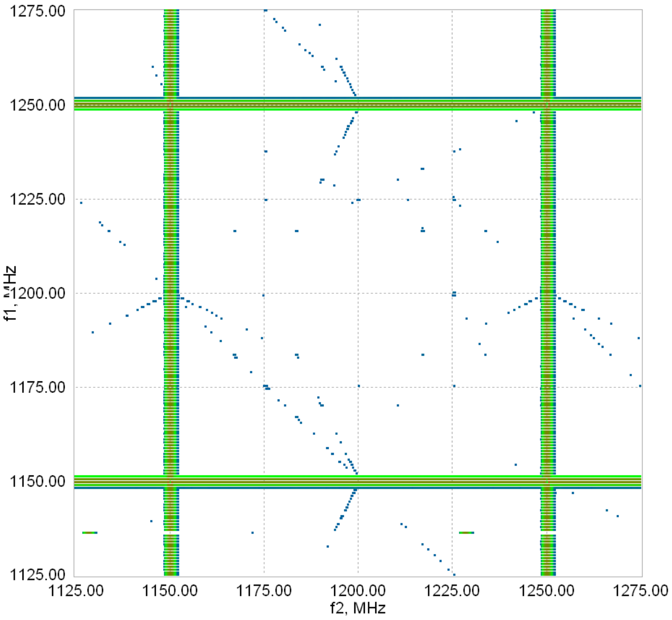

Fig. 9. DFD of mixer ZEM-4300+. The test signal levels are -22 dBm, other conditions are the same as in Fig. 6.

TABLE II. THE MAIN SPURIOUS AND INTERMODULATION RESPONSES DETECTED IN THE CENTRAL PART OF DBMS' DFDS

No	Mix order	IM order	Z1	Z2	Z3	$P_{1in} = P_{2in}$, dBm		
						Mixer's type (see Table I)		
						I	*II*	*III*
1	2	2	1	-1	0	-15.0	-15.7	**-23.2***
2	2	2	-1	1	0	-15.5	-15.9	**-23.4***
3	4	3	-2	1	1	**-19.5**	**-19.5**	**-19.1**
4	4	3	2	-1	-1	**-19.6**	**-18.9**	**-18.5**
5	4	3	1	-2	1	**-19.8**	**-18.5**	**-18.9**
6	4	3	-1	2	-1	**-19.6**	**-18.9**	**-18.5**
7	4	{2}	0	-2	2	-15.5	-10.0	**-18.5**
8	4	{2}	0	2	-2	-14.8	-11.8	**-18.6**
9	4	2	-1	-1	2	**-19.9**	-14.6	**-23.3***
10	4	2	1	1	-2	**-19.5**	-15.7	**-22.5***
11	6	{3}	0	-3	3	-15.4	-14.4	-14.8
12	6	{3}	0	3	-3	-15.4	-14.4	-14.1
13	6	3	2	1	-3	**-19.4**	**-18.9**	**-19.3**
14	6	3	1	2	-3	**-20.0**	**-19.3**	**-19.6**
15	6	3	-1	-2	3	**-19.6**	**-19.3**	**-19.6**
16	6	3	-2	-1	3	**-19.6**	**-19.3**	**-19.6**

the first and by the "virtual" higher harmonics of the LO signal. Images of these intermodulation responses are located in the periphery of the DFD given in Fig. 1 (ref. Tables II, III, IV).

RF Generator 3 used in ADFTS (ref. Fig. 1) is a modern high-quality analogue generator having very low levels of the higher harmonics in the output signal. Therefore, the anomalously high levels of a "virtual" (involved in the spurious and intermodulation responses of MUT) higher harmonics of the LO signal can be explained only by peculiarities of balanced signal conversion in DBM. This was proved experimentally: connecting the low-pass filter to the output of the Generator 3 does not change the DFDs given in Figs. 4, 6, 7, 8, 9 and susceptibilities given in Tables II, III, IV.

Input signal levels at which the image of a spurious response disappears from the DFD are 2…4 dB less than the susceptibility level for this response. E.g., the image of the spurious response (z_1, z_2, z_3) = (0, 3, -3) for mixer ZEM-4300+ is visible in the DFD measured at $P_{1in} = P_{2in} = -18$ dBm (ref. Fig. 8), but the susceptibility level for this response is of $P_{1in} = P_{2in} = -15.4$ dBm (ref. Table II). This results from the impact of internal noise of the MUT and the spectrum analyzer. The susceptibility levels are measured using a special procedure in which the impact of internal noise is reduced by the averaging technique. The DFCs are measured without averaging in order to increase the measurement speed.

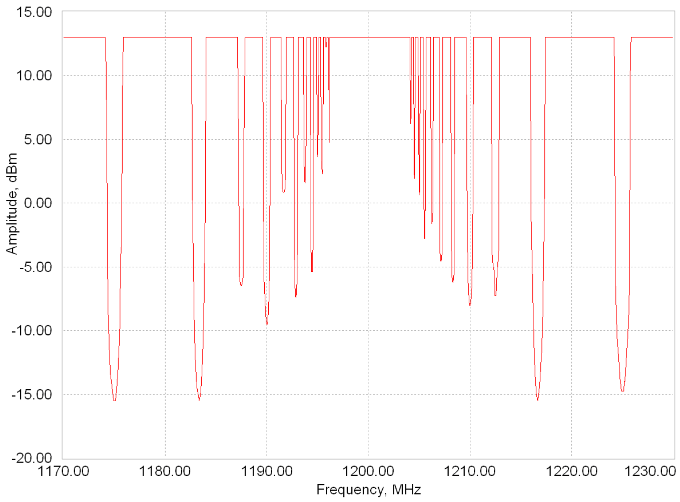

Fig. 10. Single-tone selectivity characteristic of mixer ZEM-4300+ (standard response is -70 dBm, LO drive level is 7 dBm).

The majority of spurious and intermodulation responses detected in DFDs of MUTs are recognized by the technique described in [6, 8], and the susceptibility level is measured for each response. The results are given in Tables II, III, and IV, in which: “Mix Order” is the total order of the frequency conversion, i.e., the sum $|z_1| + |z_2| + |z_3|$ of the absolute values of conversion factors in (3); “IM Order” is the intermodulation order, i.e., the sum $|z_2| + |z_2|$; and the measured level of susceptibility is designated as “$P_{1in} = P_{2in}$”.

The main low-order spurious and intermodulation responses detected in the central part of DBMs’ DFDs are characterized in Table II, in which the most dangerous responses are marked by bold type and asterisk. Note that

- only first eight responses (No. 1 to 8) are traditionally considered as the most dangerous;
- all MUTs demonstrate nearly equal susceptibility for each of the responses 3…6 and 11…16;
- with respect to the responses 1, 2, and 7…10, MUT II is the best one and MUT III is the worst (which correlates with the prices – ref. Table I);

The selectivity characteristic of MUT I (measured by changing the level of a single-tone signal at the RF input and catching the standard response level at the IF output) is shown in Fig. 10. This characteristic contains the images of spurious responses (located in the central part of the DFD given in Fig. 6) described by equation (3) with the following coefficients: $z_1 = 0$; $z_2 = z_3 = N$, where N is the number of involved LO harmonic. Note that

- the DBM susceptibilities for spurious responses (at 1175 MHz and 1225 MHz) involving the 2nd harmonic of LO signal (i.e., N = 2) and for spurious responses (at 1183 MHz and 1217 MHz) involving the 3rd harmonic (N = 3) are nearly equal (ref. Table II),
- for spurious responses involving the higher harmonics of LO signal, the DBM susceptibility decreases rather slowly with increasing N: e.g., for spurious responses (at 1193 MHz and 1207 MHz) involving the 7th harmonic of LO signal (N = 7), the susceptibility is only 10 dB less than for the responses involving the 2nd and 3rd harmonics.

The characterization results for a lot of 4th and 5th-order intermodulation responses located in the central part of the DBM’s DFD and detected at the test signal levels of approximately 10 dB above the susceptibility to intermodulation (ref. Table II) are given in Table III. Only the first six intermodulation responses (involving the first harmonic of the LO signal or not involving LO signal at all) are traditionally recognized as the most dangerous – they are marked by bold type in Table III. In view of the susceptibility levels, these responses does not appear more dangerous than the most other responses given in Table III and involving the higher (up to the 5th) harmonics of the LO signal. Again, MUT II outperforms the others.

Finally, the characterization results for the most essential 2nd- and 3rd-order-intermodulation responses and spurious responses detected in periphery of the DFD (given in Fig. 4) at the test signal levels nearly equal to the intermodulation susceptibility (ref. Table II) are summarized in Table IV. As before, the responses traditionally considered as the most dangerous are marked by bold type; but again the susceptibility levels corresponding to these responses are comparable (and sometimes equal) to the susceptibilities observed for the other responses from Table IV. MUT II has the best performance, MUTs I and III – nearly equal to each other.

TABLE III. VARIOUS INTERMODULATION RESPONSES DETECTED IN THE CENTRAL PART OF DBMS’ DFDS

No	**Mix order**	**IM order**	**Z1**	**Z2**	**Z3**	**$P_{1in} = P_{2in}$, dBm**		
						Mixer’s type (see Table I)		
						I	***II***	***III***
17	**4**	**4**	**-2**	**2**	**0**	**-12.2**	**-8.4**	**-8.5**
18	**4**	**4**	**2**	**-2**	**0**	**-12.3**	**-8.2**	**-8.6**
19	**6**	**5**	**-3**	**2**	**1**	**-12.2**	**-10.4**	**-11.4**
20	**6**	**5**	**2**	**-3**	**1**	**-12.3**	**-10.4**	**-11.4**
21	**6**	**5**	**3**	**-2**	**-1**	**-11.9**	**-10.5**	**-11.0**
22	**6**	**5**	**-2**	**3**	**-1**	**-11.8**	**-10.8**	**-11.0**
23	6	4	-1	3	-2	-10.6	-4.8	-11.0
24	6	4	-3	1	2	-11.2	-3.4	-11.0
25	6	4	3	-1	-2	-10.6	-5.0	-11.7
26	6	4	1	-3	2	-11.6	-3.8	-11.4
27	8	4	2	2	-4	-11.4	-6.2	-13.4
28	8	4	-2	-2	4	-11.6	-3.5	-13.6
29	8	4	-3	-1	4	-11.0	-0.5	-11.8
30	8	4	3	1	-4	-11.2	+0.3	-10.3
31	8	4	-1	-3	4	-11.0	-1.3	-11.8
32	8	4	1	3	-4	-11.0	-0.5	-9.5
33	8	5	1	-4	3	-11.7	-10.6	-9.9
34	8	5	-1	4	-3	-11.7	-10.8	-9.5
35	8	5	4	-1	-3	-11.7	-10.8	-9.5
36	8	5	-4	1	3	-11.6	-10.6	-9.1
37	10	5	3	2	-5	-13.5	-12.8	-12.4
38	10	5	-2	-3	5	-13.1	-12.6	-12.0
39	10	5	-3	-2	5	-13.1	-12.6	-11.6
40	10	5	2	3	-5	-11.6	-10.7	-10.5
41	10	5	1	4	-5	-11.4	-11.0	-9.1
42	10	5	-1	-4	5	-11.7	-10.8	-9.9
43	10	5	-4	-1	5	-11.6	-10.8	-9.5
44	10	5	4	1	-5	-11.7	-11.0	-9.0

If the IF is high, the images of some intermodulation responses from Table IV (which are traditionally not considered as dangerous) may move nearer to the receiver's tuning frequency (Fig. 11), which means that the IM product may fall into the preselector passband and impair the EMC.

TABLE IV. SPURIOUS AND INTERMODULATION RESPONSES DETECTED IN THE PERIPHERY OF DBMS' DFDS

No	**Mix order**	**IM order**	**Z1**	**Z2**	**Z3**	**$P_{1in} = P_{2in}$, dBm**		
						Mixer's type (see Table I)		
						I	***II***	***III***
$f_1 > f_{LO} + f_{IF}$, $f_2 > f_{LO} + f_{IF}$								
45	5	{2}	0	-2	3	-21.4	-8.6	-19.0
46	5	2	-1	-1	3	-24.5	-9.3	-22.3
47	7	3	1	2	-4	-17.4	-12.9	-17.0
48	7	3	2	1	-4	-17.0	-12.9	-17.8
49	7	3	-2	-1	4	-17.0	-9.9	-18.1
50	7	3	-1	-2	4	-17.0	-10.4	-18.1
$f_1 > f_{LO} + f_{IF}$, $f_2 < f_{LO} - f_{IF}$								
51	**3**	**{2}**	**0**	**-2**	**1**	**-23.5**	**-22.0**	**-25.0**
52	**3**	**{2}**	**0**	**2**	**-1**	**-17.5**	**-14.5**	**-14.0**
53	**3**	**2**	**-1**	**1**	**1**	**-24.5**	**-12.1**	**-20.0**
54	**3**	**3**	**-1**	**2**	**0**	**-14.0**	**-12.2**	**-17.8**
55	**3**	**3**	**1**	**-2**	**0**	**-15.1**	**-12.8**	**-17.4**
56	5	{3}	0	-3	2	-16.8	-10.0	-13.1
57	5	3	2	-1	-2	-15.5	-12.9	-18.9
58	5	3	-2	1	2	-16.6	-12.5	-17.0
$f_1 < f_{LO} - f_{IF}$, $f_2 < f_{LO} - f_{IF}$								
59	**3**	**2**	**1**	**1**	**-1**	**-23.7**	**-14.0**	**-17.8**
60	5	3	-1	-2	2	-14.0	-13.3	-17.0
61	5	3	-2	-1	2	-14.0	-13.1	-17.0
62	5	3	1	2	-2	-13.2	-11.8	-17.0
63	5	3	2	1	-2	-14.2	-12.1	-17.0

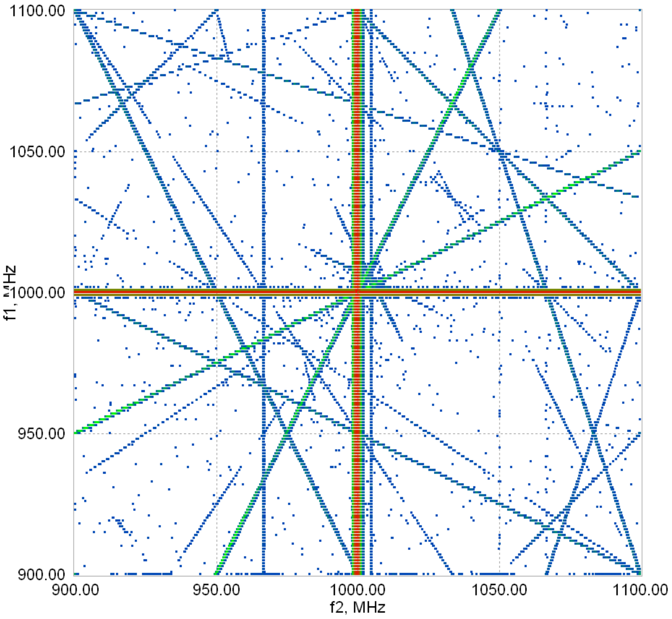

Fig. 11. DFD of mixer ZEM-4300+. The display threshold is -70 dBm, which is 6 dB above the SA noise level. The SA is tuned to f_{IF} = 300 MHz and has the bandwidth of 4 MHz. The test signal levels are $P_{1in} = P_{2in}$ = -15 dBm. The LO frequency is f_{LO} = 1300 MHz, and its level is P_{LO} = 7 dBm.

IV. CONCLUSION

Provided results of experiments demonstrate that the ADFTT makes it possible to obtain comprehensive information about the nonlinear properties of a mixer. Such information is not specified in the mixer data sheet, in which only 1-dB-compression point and (not so often) IP3 are usually given [7].

It is reasonable to use the results of mixer testing by the instrumentality of ADFTT for design of radio receivers (especially of high-quality receivers, which are able to operate in severe electromagnetic environment, e.g., in co-site complexes of radio systems): for estimating the levels of susceptibility to spurious-response and intermodulation interference (appearing if the tested mixer is included in the receiver structure), for choosing the number and values of intermediate frequencies, for justification of characteristics of receiver components (amplifiers, mixers, filters, etc.)

The peculiarity of microwave double-balanced mixers presented in this paper (a lot of intermodulation and spurious responses that are not traditionally considered as the most dangerous but are such in fact because of their high levels – ref. Section III) confirms the need to describe nonlinear properties of the receiver and its components in more details than in the traditional methods of EMC analysis and design. This need is the most urgent for receivers intended to operate in severe electromagnetic environment and for receivers having no (or a little) frequency selectivity before the first mixer. When analyzing nonlinear interference to such receivers, it is not enough to account for the traditional types of spurious and intermodulation responses, but the use of a discrete nonlinear analysis technique yields good result [9].

REFERENCES

[1] Rohde U., Whitaker J. Communications receivers: DSP, software radios, and design, 3rd ed., McGraw-Hill, 2000, 656 p.

[2] Rohde U.L., Newkirk D.P. RF/Microwave circuit design for wireless applications, John Wiley & Sons, Inc., New York, 2000, 954 p.

[3] Davydov U.T., Danich U.S., Zhukovsky A.P., Zaharov U.S., Protopopov A.S., Tsvetkov V.V. Radio receivers, "Vyschaya Shkola" Publishers, Moccow, 1989, 342 p. (in Russian)

[4] Mordachev V.I., "Automated double-frequency testing technique for mapping receiver interference responses," IEEE Trans. on EMC, vol.42, No.2, pp. 213–225, May 2000.

[5] Pedro J.K., Carvalho N.B. Intermodulation distortion in microwave and wireless circuits, Artech House, 2003, 432 p.

[6] Mordachev V.I., Sinkevich E.V. Experimental analysis of radio receiver susceptibility to out-of-band interference by means of Double-Frequency Test System, Procedings of the 10-th Int. Symp. on EMC "EMC Europe 2011", UK, York, Sept. 26-30, 2011, pp. 405-411.

[7] Data sheets of frequency mixers ZEM-4300+, ZFM-11-S+, and ZFM-5X-S+. Available: http://www.minicircuits.com

[8] E.Sinkevich. Universal technique for interference response recognition from results of radio receiver's double-frequency testing, Proceedings of the IX-th International Symposium on Electromagnetic Compatibility and Electromagnetic Ecology, Saint-Petersburg, Russia, Sept 13-16, 2011, pp.308-311.

[9] Sinkevich E., Mordachev V. Characterization of radio receiver's front-end nonlinearity by measurement of spurious-free dynamic ranges, Proceedings of the 11-th Int. Symp. on EMC "EMC Europe 2012", Rome, Italy, Sept. 17-21, 2012, 6 p.