Retrodirective Antenna Array Using High Frequency Offset

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Abstract. *The paper deals with the design of a simple retrodirective antenna array exhibiting by high frequency offset between received and transmitted wave. Analysis of the beam pointing error using antenna array model developed in MATLAB is described. The frequencies of transmitted wave and received wave are chosen on the basis of this analysis. Then a suitable structure for further design is determined and particular blocks of complete retrodirective antenna array are briefly described and their measured parameters are presented. Relatively high frequency offset between received and transmitted wave makes it possible to use frequency filters for received and transmitted signal separation which led to significant reduction of the circuit complexity.*

Keywords

Antenna array, retrodirectivity, mixer, patch antenna

1. Introduction

This paper deals with a design of a retrodirective antenna array. It means an antenna array which automatically retransmits signal to the direction of interrogator without prior knowledge of its position. Retrodirective antenna array described in this paper uses phase conjugating circuitry of signal received by particular antenna elements of this array. Principle of this technique is illustrated in Fig. 1. The received signal is phase conjugated in the mixer at each antenna element (red points in Fig. 1). Signal with conjugated phase is retransmitted by the same antenna element which received the incoming signal. Reception and transmission occur continuously in the same time. This ensures that the most energy is transmitted into the direction of the antenna array irradiation. Frequency of the received and transmitted signal is same. This principle is described in [1] in detail.

Above mentioned retrodirectivity of antenna array is assured only if ideal antennas are used. Using of real antennas leads to the beam pointing error (BPE) resulting in angular deviation between the propagation direction of received electromagnetic wave and maximum of radiation pattern of retrodirective antenna array.

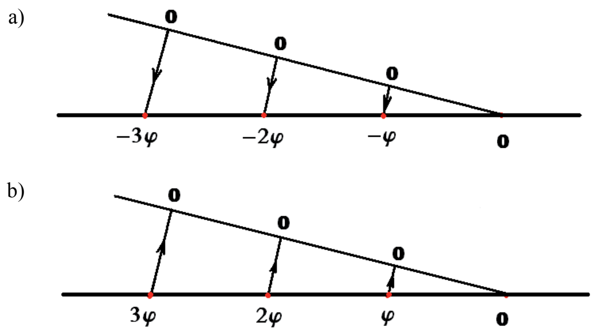

Fig. 1. Operation principle of antenna array with phase conjugating elements; a) reception, b) transmission.

The use of the different frequencies for received and transmitted wave leads also to angular deviation BPE. Orientation of this deviation depends on the relation between frequency of received signal f_{RF} and frequency of phase conjugated transmitted signal f_{IF} as is illustrated in Fig. 2.

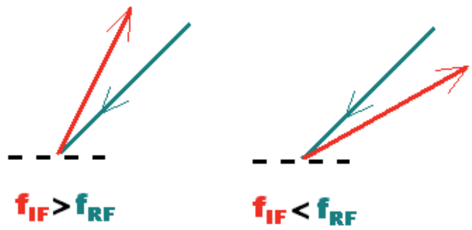

Fig. 2. Influence of different reception and transmission frequencies on BPE.

BPE caused by real antennas (with higher directivity compared to ideal antennas) can be significantly compensated if the relation between frequencies is properly chosen.

2. Analytical Model

For more detailed investigation of BPE phenomena, analytical model of four element retrodirective antenna array was developed. Each array element represents an antenna with phase conjugating device (mixer). Elements are equidistantly spaced in one row. Such model was implemented in MATLAB software. Realized script is capable to evaluate normalized bistatic and monostatic radar cross section (RCS) characteristics of retrodirective antenna array with ideal antennas and patch antennas for different antenna spacing and spatial orientation. Frequencies of received and transmitted signal can be set to arbitrary values.

Radiating function of retrodirective antenna array used in the analytical model is [2]

$$F = 2\cos\left(\frac{3}{2}d(k_{IF}\sin\Phi_{IF} - k_{RF}\sin\Phi_{RF})\right) + 2\cos\left(\frac{1}{2}d(k_{IF}\sin\Phi_{IF} - k_{RF}\sin\Phi_{RF})\right) \quad (1)$$

where Φ_{RF} is angle of the received wave direction, Φ_{IF} is angle of examination of transmitted field, d is distance between centers of patch antennas, k_{IF} is wave number for frequency of transmitted signal and k_{RF} is wave number for frequency of signal received by retrodirective antenna array. Angles Φ_{RF} and Φ_{IF} are measured from axis which is perpendicular to the antenna array plane as is illustrated for Φ_{RF} in Fig. 3.

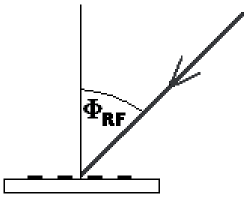

Fig. 3. Illustration of the wave direction angle.

Patch antenna analytical model equations are based on patch antenna aperture model published in [3].

Used equation for normalized radiating function in E-plane is

$$\left|\frac{F_E}{F_{E\max}}\right| = \left|\cos(\pi v_x)\right| \quad (2)$$

and in H-plane

$$\left|\frac{F_H}{F_{H\max}}\right| = \left|\cos(\theta)\frac{\sin(\pi v_y)}{\pi v_y}\right| \quad (3)$$

where

$$v_x = \frac{L}{\lambda}\sin(\theta) \quad (4)$$

and

$$v_y = \frac{W}{\lambda}\sin(\theta) \quad (5)$$

are normalized wave numbers in x and y axis direction, L and W are the patch dimensions also included in Fig. 4.

Further, for the better isolation between transmitted and received signals, a two-port dual-polarized patch antenna has been chosen as the array element. The MATLAB script was extended for the calculation of the BPE dependency on Φ_{RF} angle. This dependency is plotted in Fig. 5, where f_{rf} is the frequency of received electromagnetic wave and f_{if} is the frequency of transmitted wave.

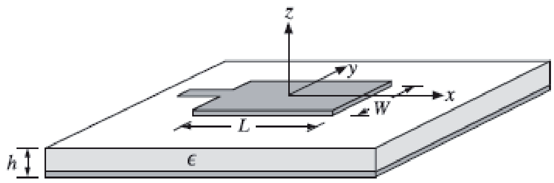

Fig. 4. Patch antenna dimension [3].

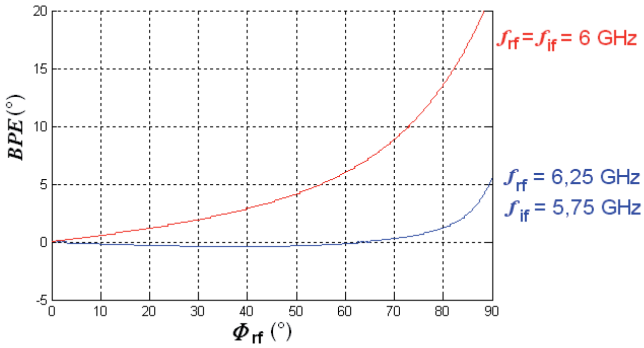

Fig. 5. Dependence of BPE on angle of direction of propagation of received wave.

Presented simulations proved that the frequencies of received and transmitted waves of the retrodirective array of patch antennas can be different. Frequency difference compensates BPE (see Fig. 5) which is caused by higher directivity of patch antennas compared to ideal omnidirectional antennas which transmit the same amount of energy to all directions in certain half space.

High frequency offset between frequency of reception and frequency of transmission makes it possible to use filters for separation of received and transmitted wave and consequently simplifies the overall complexity of the retrodirective array circuitry.

3. Design Description

For further design, four-element-array structure has been chosen. Block diagram of one element is illustrated in Fig. 6. Signal at frequency 12 GHz is distributed to all elements by Wilkinson power dividers network. Spacing between antennas is $\lambda_{rf}/2$. This ensures that grating lobes don't appear.

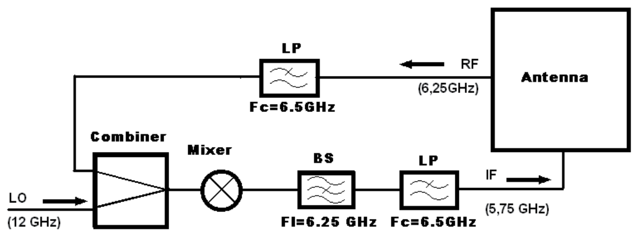

Fig. 6. Block diagram of one element of retrodirective antenna array.

All blocks from Fig. 6 has been designed and simulated using Ansoft Designer software. The patch antenna analysis has been performed also in CST Microwave studio software. All blocks were designed on the Arlon 25N substrate with thickness of 0.762 mm and their function (except Wilkinson power dividers) has been experimentally verified.

3.1 Filters

Both low pass filters are the same. They represent the stepped impedance filter of the 7th order of Chebyshev approximation.

Measurement of realized low pass filter has proved that 12GHz signal is suppressed approximately by 60 dB. Both signals, RF and IF, are in the pass band.

Band stop filter is of the two dual mode E-shaped resonators type. Its detailed description can be found in [4]. Filter dimensions are labeled in Fig. 7. Their values for optimized filter are listed in Tab. 1. By measuring of the realized device the signal suppression 20 dB at 6.25 GHz has been detected.

Lc	*w*	*Lf*	*Lcw*	*g*	*d*	*ls*	*s*
[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]
4.78	0.90	2.05	4.61	0.20	19.30	12	5.32

Tab. 1. Dimensions of band-stop filter.

Impedance matching at frequency 5.75 GHz has been improved by open-ended stub connected to 50 Ω transmission line on the filter input. The characteristic impedance of the stub is 50 Ω. The length of the stub *ls* and the distance from resonators *s* are also included in Tab. 1. Measurements of the improved filter show that the $|S_{11}|$ is approximately –20 dB and $|S_{22}|$ is lower than –25 dB at frequency 5.75 GHz.

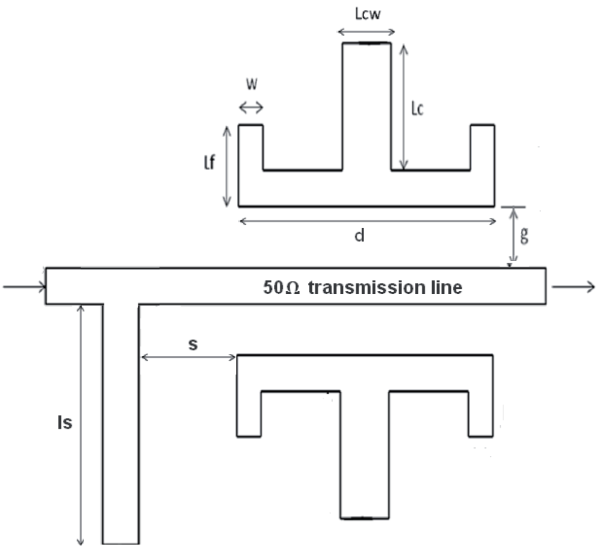

Fig. 7. Band-stop filter layout and dimension labels.

3.2 Mixer and Combiner

The layout of the designed mixer and combiner with low pass filter is depicted in Fig. 8. It is the active mixer with ATF–36163 PHEMT transistor. The nonlinear Raytheon – Statz model has been used in design of the matching networks and for determining of the expected gain. The phase conjugating operation of this mixer model was verified using Ansoft Designer.

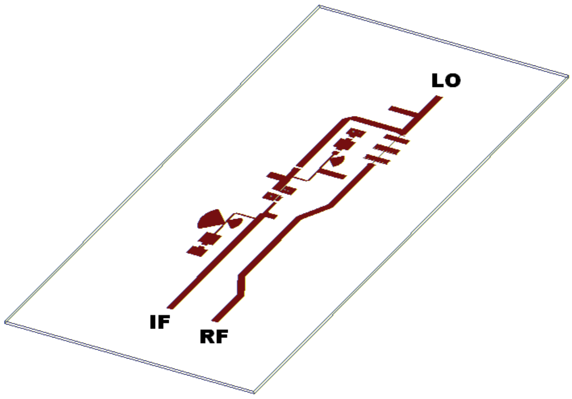

Fig. 8. Mixer with combiner layout.

Two versions of the mixer with slightly different matching lines have been manufactured on the same substrate together with the band-stop filter (see Fig. 9). Transmission line between the RF port and the low pass filter of the combiner is bended. This modification is only because of measurement requirements. Measured insertion loss between RF and LO ports at frequency 6.25 GHz is approximately 32 dB. RF signal transmission to LO port is suppressed by the open-ended stub with quarter-wave resonance at frequency f_{RF} = 6.25 GHz at $\lambda_{RF}/4$ distance from the combiner T-junction. Measured insertion loss between LO and RF ports at 12 GHz is approximately 30 dB.

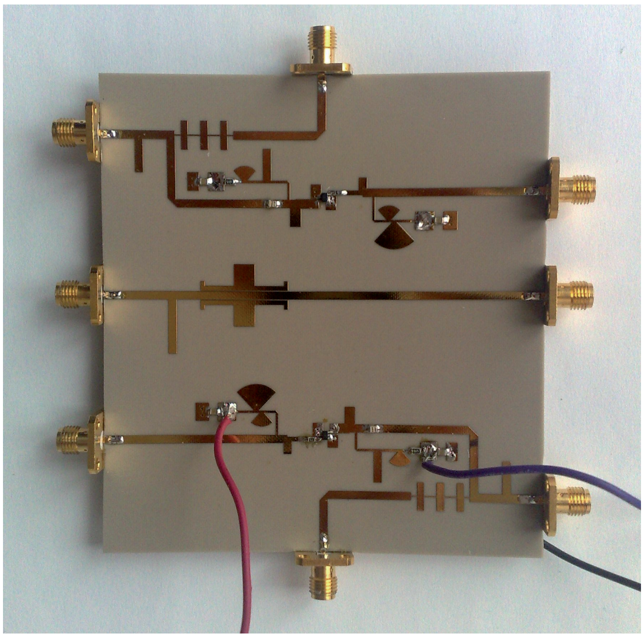

Fig. 9. Mixers and band-stop filter realization.

Measured conversion gain of the realized mixer was 4.5 dB. The input compression point IP1dB = –4 dB. The measured spectrum at the mixer output is depicted in Fig. 10. This signal is filtered by the band stop and low pass filters prior transmission in the complete retrodirective antenna array.

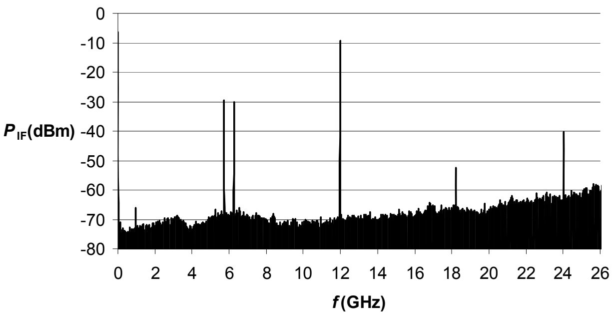

Fig. 10. Measured spectrum at the mixer output.

The difference between power of the RF and IF signals is only 0.5 dB at the mixer output. RF - IF isolation approximately 20 dB can be achieved using the bandstop filter described above. LO signal at 12 GHz from the oscillator can be sufficiently suppressed by the lowpass filter mentioned above.

3.3 Patch Antenna

The designed retrodirective antenna array uses dual-polarized two-port patch antennas; RF port for reception and IF port for transmission. Improvement of the isolation between the received and transmitted waves is achieved by polarization discrimination. Patch antennas fed by electromagnetic coupling (EMC) method has been chosen. This variant is easy to manufacture and makes it possible to make some adjustments after fabrication, because patches are made on a different board than feeding transmission lines. EMC fed patch antenna has been manufactured on a separate substrate (see Fig. 11).

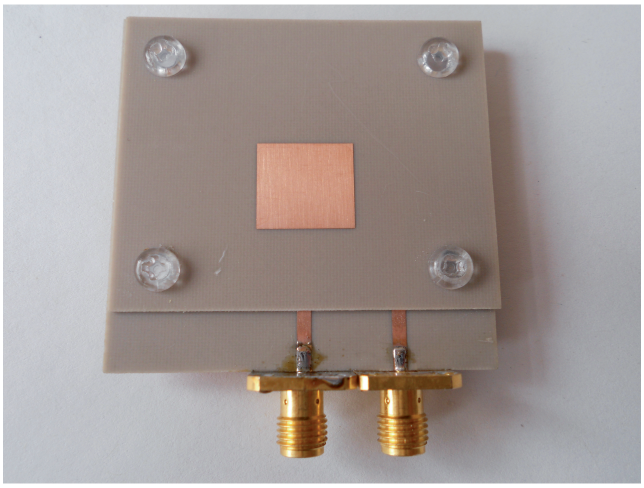

Fig. 11. EMC fed patch antenna realization.

Return loss of the realized antenna is higher than 20 dB at both RF and IF ports. Measured gain of the antenna is 6 dB for both ports. Normalized radiation patterns in decibels for both RF and IF port are depicted in Fig. 12 and Fig. 13. The patterns are slightly asymmetrical due to vicinity of the feeding lines and the patch.

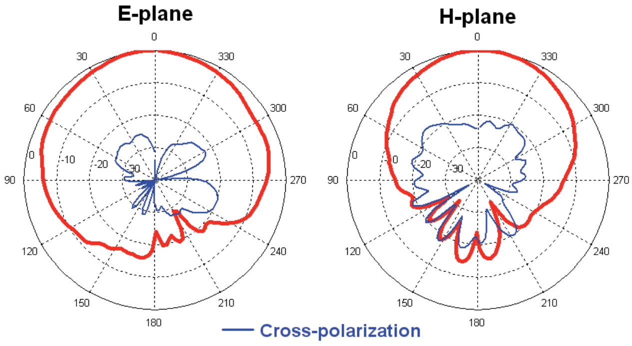

Fig. 12. Normalized radiation patterns; RF port.

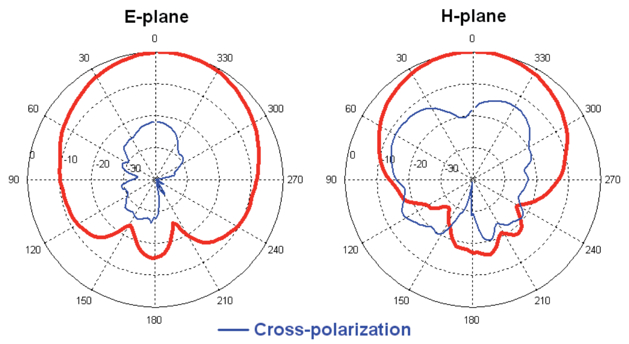

Fig. 13. Normalized radiation patterns; IF port.

Radiation patterns of the designed retrodirective antenna array in the plane where retrodirectivity occurs is influenced by RF port H-plane radiation pattern and IF port E-plane radiation pattern. These measured characteristics have been imported to MATLAB script instead of analytical model of patch antenna and results has been compared with purely analytical model.

The simulated four elements retrodirective antenna array field radiation patterns for $\Phi_{rf} = 30°$ are in Fig. 14. The small angular deviation between the purely analytical model and the model with the measured patch antenna characteristics is evident. The reasons are narrower radiation patterns and asymmetry in IF-port E-plane radiation pattern of the measured antenna compared to the analytical model.

Comparison of monostatic RCS characteristics as results of the purely analytical model and the model with the measured antenna characteristics is presented in Fig. 15. The influence of the asymmetry in patch antenna radiation patterns is evident.

Better results of the complete retrodirective array can be expected, because of the larger ground plane around the patch antennas.

The complete retrodirective antenna array proposal is depicted in Fig. 16. Spacing between antennas is $\lambda_{rf}/2$. The dimensions of complete array PCB are approximately 180×125 mm^2.

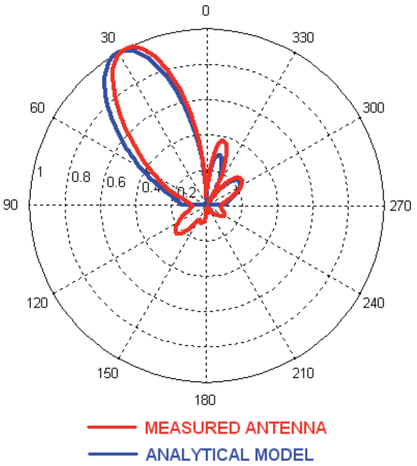

Fig. 14. Simulated field radiation pattern, Φ_{rf} = 30°.

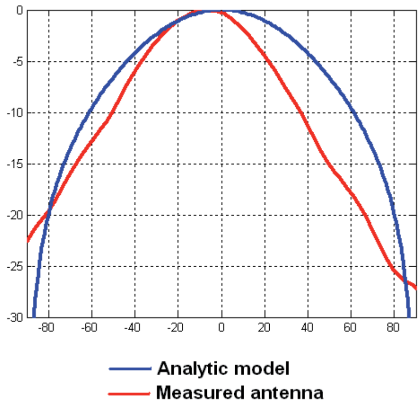

Fig. 15. Relative monostatic RCS characteristics.

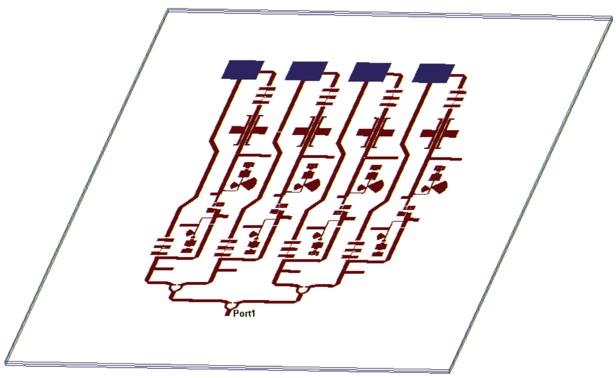

Fig. 16. Retrodirective antenna array proposal.

4. Conclusions

In term of convectional theory, the retrodirective antenna arrays use same frequencies for reception and transmission. Theory also considers ideal antennas which act as isotropic radiator in required half-space. Most of previously published retrodirective antenna arrays use only slightly different frequencies (for example [5] and [6]).

Using of real antennas and different frequencies for reception and transmission leads to BPE. BPE caused by real antennas can be partly compensated if the transmitting and receiving frequencies are properly chosen.

For detailed examination of BPE phenomenon, analytical model of four-element retrodirective antenna array has been created using MATLAB. On the basis of this model, frequencies for transmission and reception of the retrodirective antenna array using dual-polarized patch antennas with polarization discrimination of received and transmitted wave has been chosen.

The frequency offset is relatively high. It makes it possible to use frequency filters for received and transmitted signal separation. The block structure of the novel retrodirective antenna array has been shown. Each block of the proposed retrodirective antenna array has been designed and manufactured separately. Their characteristics are briefly mentioned in this paper.

The designed mixer conversion gain is 4.5 dB and approximately 20 dB RF-IF isolation can be achieved with the band-stop filter which is described in this paper. These results are similar to previously published mixers in [7], but the design proposed in this paper is less space-consuming. It can be realized also on substrates with relatively low permittivity and simultaneously keeps the required $\lambda_{rf}/2$ spacing between antennas.

Acknowledgements

The support of the projects CZ.1.07/2.3.00/20.0007 WICOMT, financed from the operational program Education for competitiveness, and FR-TI3/447, financed from the Ministry of Industry and Trade of the Czech Republic are gratefully acknowledged. The described research was performed in laboratories supported by the SIX project; the registration number CZ.1.05/2.1.00/03.0072, the operational program Research and Development for Innovation.

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