Microwave Radar Sensor Based on CRLH SIW Leaky-Wave Antennas

Filip Kozak, Vojtech Jenik, Jan Machac and Premysl Hudec
Czech Technical University in Prague,
Faculty of Electrical Engineering, Department of Electromagnetic Field,
Technicka 2, 166 27, Prague , Czech republic,
Email: kozakfi1@fel.cvut.cz, hudecp@fel.cvut.cz

***Abstract*—Modern methods of active defense of military vehicles are based on detection of threat missiles and their elimination by suitable active counter-measures. For these purposes, special radar detection systems are often used. The presented solution employs the SIW based leaky wave antennas which enable detection of the threat missiles in an immediate vicinity of the protected vehicle. The missiles are detected by two tilted detection planes: one main detection plane (as described in [1]), and the other, operating ahead of the main plane. Since the missiles fly through two different planes set under two different angles, system triggering can be improved and more missile parameters can be measured. The sensor structure is relatively simple and occupies merely little space on the surface of the protected vehicle. The performed tests prove functionality of the developed solution.**

***Keywords*—Active defense, radar sensor, sensor system, leaky-wave antenna, SIW.**

I. INTRODUCTION

The design of the presented microwave sensor was elaborated when developing the radar sensors for active defense (AD) of military vehicles. Generally, the AD systems are based on detection of approaching threat missiles (TMs) and activation of suitable counter-missiles able to destroy, deflect or de-activate the former one. Nowadays, great attention is paid to systems capable of operation even in the complex urban environment, where TMs can be shot from immediate distances from the vehicle, typically from even less than 20 meters. This task is insoluble by standard AD systems based on middle-range surveillance radars. One possible solution can be based on the 'microwave curtain' concept; its basic description can be found e.g. in [1] and [2].

The 'microwave curtain' (MC) can be formed by a set of microwave sensors equipped with antennas showing wide radiation patterns in the horizontal plane and relatively narrow radiation patterns in the vertical plane. A set of these antennas is fixed around the protected vehicle, while the maxima of their radiation patterns are tilted under the angle α_P, see Fig. 1.

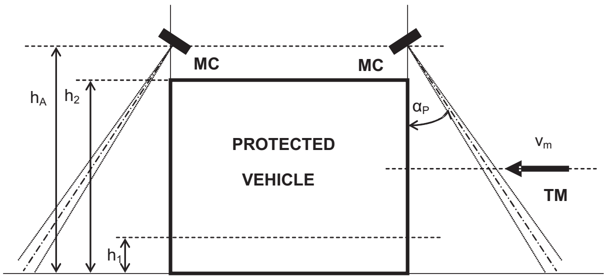

Fig. 1. Basic microwave curtain structure.

If the TM enters the detection plane in question, the connected radar sensors generate output signals that can be further processed and used for generation of triggering signals capable of activating suitable counter-measure or for calculation of important TM parameters. This concerns especially identification of the detected target, measurement of its speed, and estimation of its potential point-of-impact. The MC is able to contribute to identification of any target, for example, by analyzing Doppler signals generated during the flight of target through the detection plane. Depending on the length and complexity of the assessed missiles, the corresponding time-dependences and spectrograms show significant differences. Analysis of signals from several neighbouring MC sensors can contribute to the estimation of point-of-impact. The above-stated assumptions have been verified by practical tests indicated in [3].

The inability to perform the above-described functions simultaneously can be considered a major problem of the MC concept. For instance, when using the MC as a trigger, it cannot be used for identification purposes. During the identification process, the missile has to pass through the entire detection plane (antenna radiation pattern) and thus gets too close to the vehicle. In addition, the fixed detection plane angle can give rise to difficulties with higher elevations of the incoming TMs. The majority of these problems can be solved by using the novel MC version based on leaky-wave antennas (LWAs).

II. LEAKY-WAVE ANTENNA SENSOR

The principal property of LWAs consists in their ability to change radiation patterns by altering the operating frequency. Owing to the design of a 1D antenna-array of this type and its vertical fastening, it is possible to turn out the required wide radiation pattern in the horizontal plane and relatively narrow radiation pattern in the vertical plane. Furthermore, the tilt of peak radiation pattern in the vertical plane can be varied by changing the operating frequency, see Fig. 5.

It can be to our advantage to use these phenomena to construct the MC sensors. Firstly, if needed, the tilt angle α_P can be easily changed e.g. according to the information on the elevation of incoming target, obtained from the surveillance radar. Secondly, it is possible to construct a multi-level MC

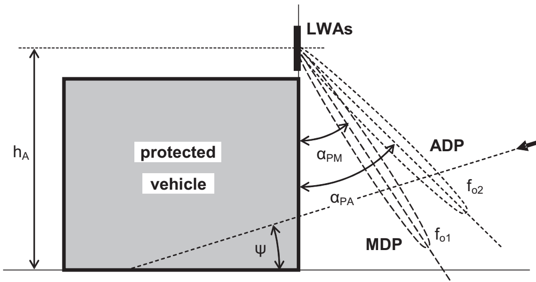

Fig. 2. Dual-plane MC - basic structure.

with 2 (or theoretically even more) detection planes with different α_P tilts; see Fig. 2.

The above-presented figure shows the dual-level MC formed by LWAs operated at two selected frequencies. One operating frequency f_{0M} can be selected so that the corresponding radiation pattern reaches its maximum in the plane tilted by α_{PM}, and forms the main detection plane (MDP). The other operating frequency f_{0A} can be chosen so that the corresponding radiation pattern attains its maximum in the plane tilted by α_{PA}, and forms the advance detection plane (ADP). The LWAs and operating frequencies can be designed in a way that the proper tilts of both planes can be obtained with an advantageous vertical orientation of all antennas. Besides, both tilts can be finely tuned in case of slightly different antenna mounting.

The designed dual-plane MC have several positive features. Above all, the structure enables to use more MC functions simultaneously. For instance, since the advance detection plane monitors objects in longer distance, it can be employed for identification of the TM, or can provide information contributing to calculation of the point-of-impact. In parallel, the main detection plane can be operated as a precise trigger. Moreover, the dual-plane MC is capable of providing more information on the TM. For example, if it flies perpendicularly to the vehicle and the radar sensors are able to measure precisely both, the Doppler frequency f_{dA} of advance detection plane and the Doppler frequency f_{dM} of the main detection plane, the following formulae can be compiled:

$$f_{dA} = \frac{2 f_{oA} v_m \cos(\psi + \pi/2 - \alpha_{PA})}{c} \tag{1}$$

$$f_{dM} = \frac{2 f_{oM} v_m \cos(\psi + \pi/2 - \alpha_{PM})}{c} \tag{2}$$

Provided that the values f_{0M} , f_{0A} , α_{PM} and α_{PA} are known, it is possible to calculate the velocity of missile v_m and elevation ψ. More general trajectory angles can be treated by using additional information provided by the near-range surveillance radar or more MCs located in the vicinity.

Fig. 3 depicts the block diagram of one possible dual-plane MC configuration. The test sensor is based on the bi-static structure, employs two LWAs and coherent down-conversion, and includes two transmitters and two receivers. The TXM transmitter and RXM receiver operate at f_{0M}, while the TXA transmitter and RXA receiver operate at f_{0A}. If both transmitters radiate simple CW signals, the $\mathrm{OUT_M}$ output provides the Doppler signal equivalent to the main detection plane, while the $\mathrm{OUT_A}$ output generates the Doppler signal corresponding to the advance detection plane. Radars with more complex (but relatively narrowband) modulation schemes can also be utilized.

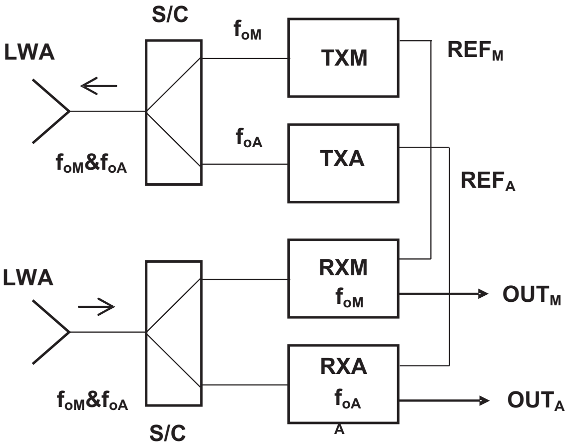

Fig. 3. Dual-plane MC - block diagram.

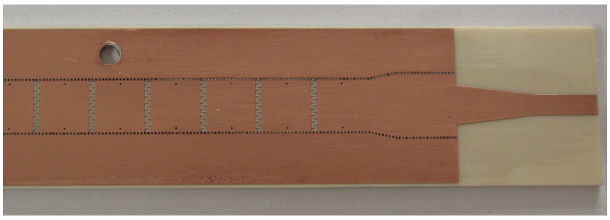

Fig. 4. Part of manufactured LWA array with visible cells.

III. LEAKY-WAVE ANTENNA DESIGN

The structure of the designed CRLH SIW-based antenna was derived from the one published in [4]. The angle of maximum radiation can be calculated by using the following formula:

$$\cos\theta = \frac{\beta}{k_0} \tag{3}$$

In this formula, β represents the phase constant of wave propagating along the antenna, while k_0 stands for the free space phase constant. The SIW was designed on the Rogers RO4003C substrate with the thickness $h = 1.524\,\mathrm{mm}$ and permittivity $\epsilon_r = 3.38$. The LWA structure consists of 26 CRLH cells; several of them can be seen in Fig. 4. The SIW width is equal to 9 mm, while the cell length attains 9.5 mm. The antenna radiates through meander slots representing series capacitors of the CRLH line equivalent circuit. Shunt inductors are constituted by two shunt inductive posts located in each SIW cell. The operating frequency band is defined by dispersion characteristics calculated using the CST Microwave Studio eigen mode solver. The free space phase constant limits the operating frequency band from about 8.6 GHz to 11.7 GHz.

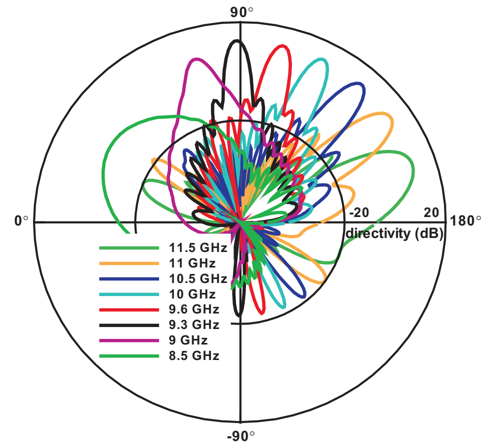

Fig. 5. LWA radiation patterns as function of operating frequency - calculated with the help of CST Microwave Studio.

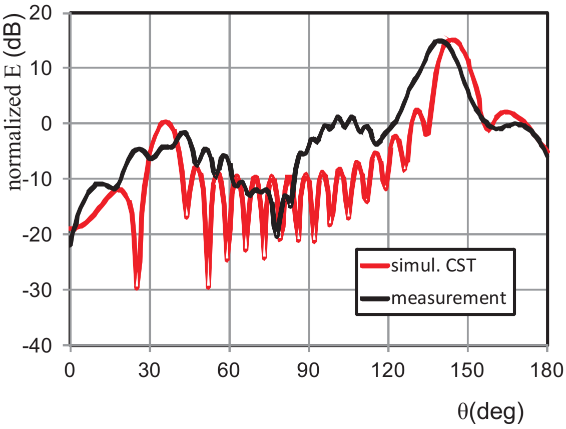

Fig. 6. Comparison of measured and simulated LWA radiation patterns at frequency 11 GHz.

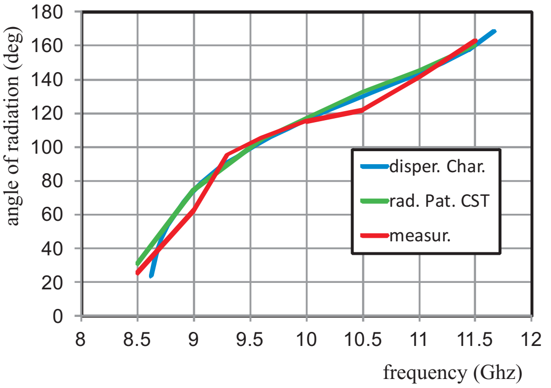

Fig. 7. Peak LWA radiation angle as function of operating frequency.

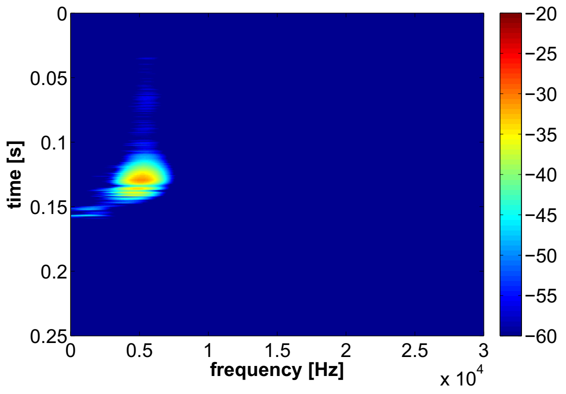

Fig. 8. Spectrogram coresponding to flight of crossbow arrow - ahead detection plane radar signal

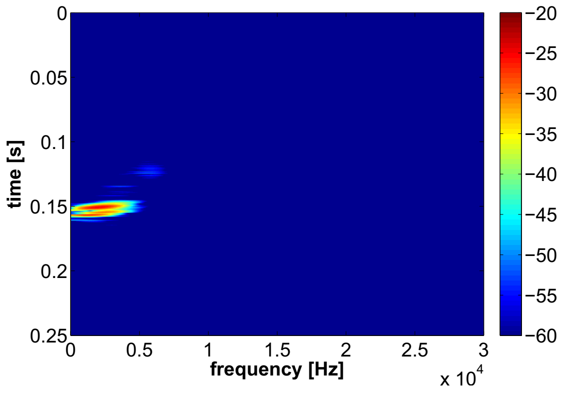

Fig. 9. Specrogram corresponding to flight of crossbow arrow - main detection plane radar signal.

When the operation frequency is changed, the main lobe of antenna radiation pattern varies continuously from approximately 35 to 165; see Fig. 5. The comparison of simulated and measured radiation patterns at the frequency of 11 GHz is presented in Fig. 6, Fig. 7 contains the frequency dependences of the LWA peak radiation angle calculated according to (3). They were deducted from Fig. 5 and read from the measured radiation patterns. The agreement among all 3 plotted characteristics seems to be acceptable.

IV. MEASURED RESULTS

The designed dual-plane MC concept was tested using a relatively simple CW radar structure, see Fig. 3. Both transmitting channels TXM and TXA consist of the PLL based oscillator, power amplifier and output splitter that divides the output signal between main and reference outputs. Both receiving channels RXM and RXA consist of the LNA and mixer fed by the corresponding $\mathrm{REF_A}$ or $\mathrm{REF_M}$ reference signals. After filtering and amplification, the base-band signal at the $\mathrm{OUT_M}$ output corresponds to the Doppler signal of the main detection plane, while the base-band signal at the $\mathrm{OUT_A}$ output corresponds to the Doppler signal of the advance detection plane. The operating frequencies were set to $f_{0M} = 11.4\,\mathrm{GHz}$ and $f_{0A} = 10.2\,\mathrm{GHz}$. During the tests, two different types of targets were applied - 9 mm bullets simulating small targets (which should be ignored by the AD system) and 50 cm long arrows shot from the crossbow that simulate larger TMs. Fig. 8 and Fig. 9 demonstrate the spectrograms equivalent to the detected flight of the 50 cm arrow.

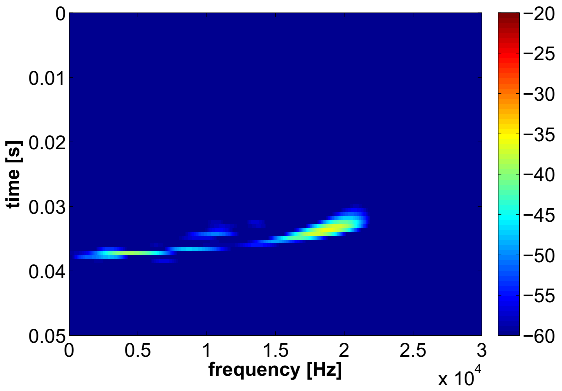

Fig. 10. Spectrogram coresponding to flight of 9 mm bullet - ahead detection plane radar signal.

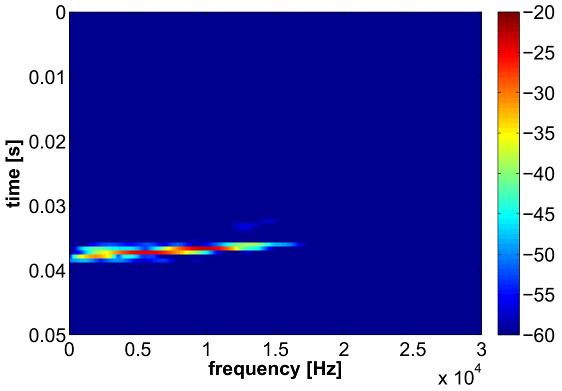

Fig. 11. Spectrogram coresponding to flight of 9 mm bullet - main detection plane radar signal.

The spectrogram of the advance detection plane signal shows approx. 30 ms long time-record. The peak Doppler frequency reaches $f_{dA} = 7\,\text{kHz}$ (measured by the advance detection plane radar), and $f_{dM} = 3\,\text{kHz}$ (measured by the main detection plane radar). Fig. 10 and Fig. 11 depict the spectrograms equivalent to flight of the 9 mm bullet. The spectrogram of advance-plane signal has approx. 3 ms long time-record, the peak Doppler frequencies reach values $f_{dA} = 20\,\text{kHz}$ (when measured by the advance detection plane radar) and $f_{dM} = 13\,\text{kHz}$ (when measured by the main detection plane radar).

Verification of the dual-plane MC concept and its capability to discriminate between small innocent bullets and larger TMs, represented the main intentions of the above described preliminary tests. Theses goals were successfully met, the developed radar sensor is able to detect the TMs in 2 detection planes and contribute to their identification. For evaluation of other capabilities of concerned sensors, new tests with 2 neighboring dual-plane MCs are being prepared.

V. CONCLUSION

The developed radar sensor benefits from exceptional properties of the leaky-wave antennas. When operated at two different selected frequencies, the antennas form the microwave curtain with two different detection planes that are subject to two different tilts. At first the approaching TM is detected by the advance detection plane radar and later by the main detection plane radar. Apart from generating precise triggering signals, this structure can contribute to both identification of the approaching target and calculation of important target parameters. The developed dual-level MC concept was verified via performed practical tests. The follow-up efforts are going to be focused especially on improving LWA radiation patterns and optimization of detection plane tilts.

ACKNOWLEDGMENT

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REFERENCES

[1] Hudec, P.; Raboch, J.; Randus, M.; Hoffmann, K.; Holub, A.; Svanda, M.; Polivka, Milan, ”Microwave radar sensors for active defense systems,” *Radar Conference, 2009. EuRAD 2009. European* , vol., no., pp.581,584, Sept. 30 2009-Oct. 2 2009

[2] Hudec, P.; Plasil, J.; Dohnal, P., ”Digital signal processing applied to radar sensors operated in active defense systems,”*Radar Conference (EuRAD), 2010 European*, vol., no., pp.483,486, Sept. 30 2010-Oct. 1 2010

[3] Jenik, V.; Hudec, P., ”Design and testing of multi-sensor radar microwave curtain,” *Radar Conference (EuRAD), 2011 European*, vol., no., pp.293,296, 12-14 Oct. 2011

[4] Y. D. Dong, and T. Itoh, ”Composite Right/Left-Handed Substrate Integrated Waveguide and Half Mode Substrate Integrated Waveguide Leaky-Wave Structures,” IEEE Trans. on Antennas Propagat., Vol. 59, No. 3, March 2011,pp.767-775.