VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
FACULTY OF FUNDAMENTAL SCIENCES
DEPARTMENT OF PHYSICS

TESTING OF ELECTROMAGNETIC RADIATION RESONATOR-CONVERTER PROTOTYPE

Phase II Report

Customer

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1. INTRODUCTION

The aim of the work is to test optical properties of the resonator-converter (R-C) prototype operating in the regimes of optical transmission and optical reflection. In phase I, optical transmission and reflectance properties of three types of R-Cs (Aires Black Crystal, Aires Shield and Aires Defender) were tested. We found that in regime of optical reflection of electromagnetic radiation (EMR) some part of an incident electromagnetic (EM) wave energy backscattered (or reflected) by the R-C. The reflected signal we registered using 8 GHz bandwidth receiver. As confirmed by the simulation results obtained by our project partners, both an incident EM wave and the EM wave reflected from R-C surface interfere with each other. The product of interference is an EM wave with a frequency and phase different from the frequency and phase of both the incident and the reflected (backscattered) EM waves.

The regime of optical reflectance of R-C works most efficiently if the R-C positioned right against the source of the EM waves (transmitter). Minimum registered power of 0.9 ÷ 2.5 GHz waves necessary for excitation of R-C, E_{min}, is 0.9 GHz ≥ 2 W. Increasing the frequency of waves emitted by the transmitter (*i. e.*, photon energy $h\nu$) and wave intensity, it was found that E_{min} is proportional to $h\nu$ and E^2. Here E^2 is the square of the amplitude of electric field vector of an incident EM wave or proportional to Poynting vector representing the directional energy flux (the energy transfer per unit area per unit time) of an EM field.

In order to test the efficiency, the change in EMR power was measured with R-C positioned at the distance of 2 – 10 λ (here λ is the central wavelength of frequency bandwidth of an incident EM wave) from the receiver, which alternates between optical transmission and optical reflectance regimes. With a fixed distance between the receiver and the R-C and moving them both away from the source, it was found that in the optical transmission regime, the outcome of R-C interaction with EM wave is very similar to that of a metal plate, screening the falling EM wave electric component. However, the interaction is different in optical reflectance regime. The EM wave reflected during such interaction interferes with an incident wave and as a result, the amplitude of incident wave of fixed at 0.9 ÷ 2.5 GHz frequency bandwidth decreased on average by 20 percent. Maximum R-C efficiency was observed in optical reflectance regime if the distance between the R-C and the receiver is below 3 λ.

Research objectives

- To test the electric properties of individual EMR R-Cs and the same properties of a group of R-Cs of the same type (devices) versus frequency band of incident EM waves in frequency bandwidth 0 ÷ 8 GHz. To measure and estimate the backscattered power and the onset power of our devices and its dependence on frequency bandwidth of incident EM waves and the device's size as well as damping of incident EM signal efficiency for different group of R-Cs when the R-C located in near-field and far-field zones in respect to source of radiation.
- To place an order with Aires Technologies for production of several Aires Black Crystal, Aires Shield and Aires Defender R-Cs having similar dimensions and antenna shape. By selecting R-Cs having minimum dispersion of parameters, to build the arrays of R-Cs and to use these R-C arrays for our future experiments.

2. METHODS

In this phase, the electric properties of R-C groups of the types specified in Phase I Report were tested in 0 ÷ 8 GHz frequency range. A group is comprised of four R-C of the same type placed at the same distance x from each other and attached to a rectangular panel transparent for electromagnetic waves of 0 - 8 GHz frequency. Optical transmission of R-C groups not exceeding 8 % was assessed by analyzing the results of experiments. Group (a) is comprised of four Aires Black Crystal R-Cs attached to a rectangular panel transparent for EM waves (Fig. 1a) and group (b) is comprised of four Aires Shield R-Cs attached to a rectangular panel transparent for EM waves (Fig. 1b). For both groups the coordinates of geometric centers of the R-Cs on the panels were the following: $x, y = \begin{pmatrix} 0,2\lambda & 2\lambda, 2\lambda \\ 0,0 & 2\lambda,0 \end{pmatrix}$ (Fig. 1).

Experiments done at VGTU Photovoltaic Technology Laboratory of Vilnius Gediminas Technical University using EM wave sources of different power (the "sources") and measuring the power, amplitude and bandwidth of incident, reflected and passed through the R-C signals using the Signal Hound Spectrum analyzer (receiver) in the 0 - 8 GHz frequency range. The frequency band of the received signal was divided it into its frequency components by means of the FFT (Fast Fourier Transformation) software which is built-in the receiver.

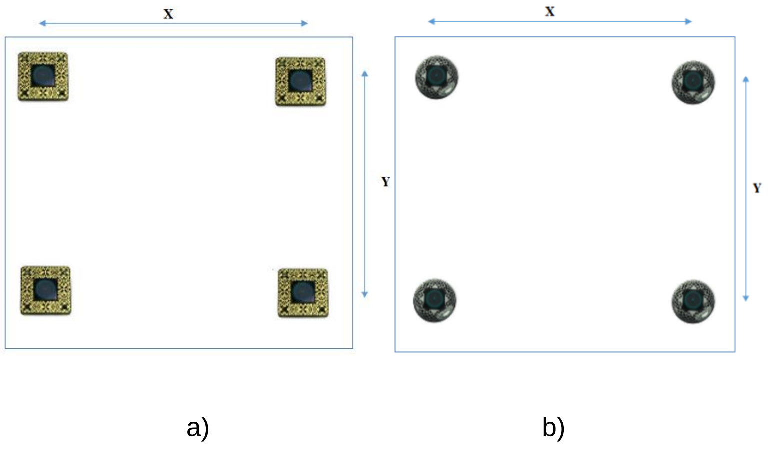

Fig. 1 Group of resonators-converters: a) type of Aires Black Crystal; b) type of Aires Shield.

The experimental scheme for measurement of amplitude/power of transmitted and reflected EM waves by different groups of R-Cs positioned at a distance ranging between 2 λ and 10 λ from the signals receiver shown in Fig. 2a for the regime of optical transmission and in Fig. 2b for the regime of optical reflection. In all related experiments, the receiver and the R-C kept at constant distance in respect to each other and both of them moved away simultaneously from the radiation source (see Fig. 2). We chose the 800 W power radiation source emitting EM waves with the center frequency of 2.5 GHz for our measurements.

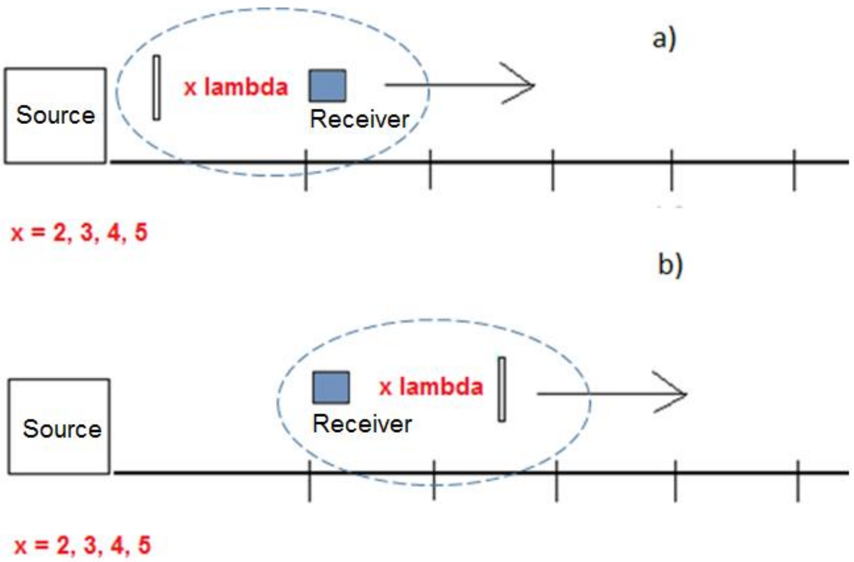

Fig. 2 Experimental schemes for the testing of radiation power of the radiation source. The resonator-converter positioned at the distance of 2 λ - 10 λ in the regimes of: a) optical transmission and b) optical reflection.

0.5 ÷ 800 W power sources used for our experiments:

Source No. 1: power **0.5 W**, central frequency of radiation **0.9 GHz**;

Source No. 2: power **2 W**, central frequency of radiation **0.9 GHz**;

Source No. 3: power **400 W**, central frequency of radiation **2.5 GHz**;

Source No. 4: power **800 W**, central frequency of radiation **2.5 GHz**.

Analyzing the way how the R-C affects the radiation power and bandwidth of the EMR emitted by a radiation source we measured the characteristic distances from the R-C at which the reflected amplitude of an incident EM wave decreased for *e* times (characteristic decay). The characteristic decay of reflected signal we calculated using experimentally measured curves of a decay of relative amplitude/power of reflected signal from the R-C versus distance from this R-C and the dependence of the relative power passed through R-C and reflected from the surface of R-C versus the distance to the source of EMR. A comparison of amplitude/power characteristic decays measured for different types of R-Cs let us to estimate the efficiency of different groups of R-C at fixed incident power of EMR source exhibiting fixed frequency bandwidth with fixed central frequency.

3. RESULTS AND DISCUSSION

The density of EM energy flux we measured at fixed positions in the space having the R-C (Aires Defender) mounted directly on the surface of the source (in the optical transmission mode) ($P_{R\text{-}C}$) and having no the R-C (P_0) in between the radiation source and signals receiver. The results shown in Fig. 3 represent semi-log plot of relative irradiance expressed as $\Delta P = P_0 - P_{R\text{-}C}$ at different distances (given in λ-as) between receiver and radiation source when both together the receiver and R-Cs move from the radiation source.

The irradiance per unit solid angle in the source surrounding environment ($\varepsilon = 1$) can be assessed by the following relationship:

$$P = 2{,}56 \cdot N \cdot G / (4\pi \cdot r^2), \tag{1}$$

here *N* is the power of electromagnetic waves emitted by the source, [*N*] = W; *G* is the antenna gain, *r* is the distance between the source and the receiver, [*r*] = m.

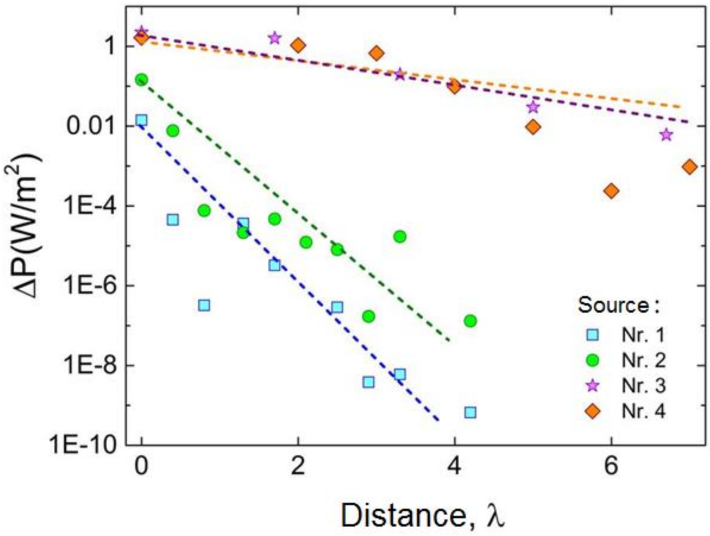

Fig. 3 A semi-log plot of the relative irradiance of 4 radiation sources versus the distance from a source to the receiver with the resonator-converter, positioned at a fixed distance from the receiver. Dotted lines represent semi-log plot of calculations of $\Delta P = P_0 - P_{R\text{-}C}$ versus distance for each case of the radiation source.

The emission power sources No. **1** and **2** emitting frequency band with a central frequency 0.9 GHz is lower than the threshold value required for the excitation of the tested R-C (Aires Defender), which has been determined as ~2 W (see Phase I project report). As the receiver and R-C are moved away from the source at a distance of 1 λ, the signal amplitude drops below the sensitivity threshold of the receiver (~1×10^{-8} W/m^2). Thus, signals of the sours the receiver receives only if it positioned at distances below 4 λ from the radiation source. The irradiance amplitude decays with increasing distance from the radiation sources in the case of both types of sources (see dashed lines in Fig. 3) look almost parallel to each other.

The irradiance of the source with 2.5 GHz central frequency (i.e. sources No. **3** and **4**) is considerably higher than the threshold value required for the excitation of the R-C. In this case both decays of Δ*P* with increasing distance from the source are much weaker (Fig. 4), what indicates different nature of these dependences than that one of the sources No. 1 and 2.

Center radiation frequency of the emitted frequency band of sources No. 3 and 4 is of 2.5 times higher than that one emitted by sources No. 1 and 2 at several hundreds of times lower radiation power. We believe that the radiation power versus the distance between the R-C and the source (Fig. 3 and 4) dependences could be explained by means of onset of the R-C (i.e. it's excitation by incident EM wave) for radiation EM waves with a central frequency dependent on dimensions of the fractal antenna built inside the R-C. Thus, at incident power exceeding ~2W the R-C turns into a source of EM waves with frequency band and central frequency of radiation dependent on R-C antenna characteristics like those of the internal structure of antenna fractals.

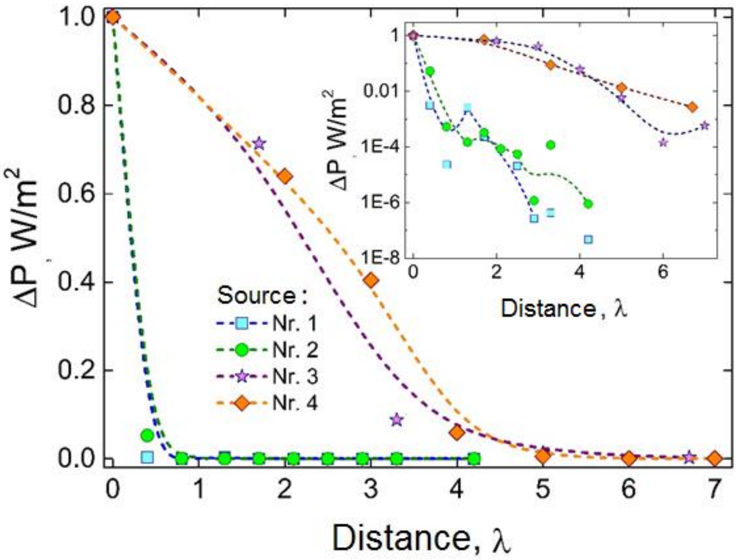

Fig. 4 The irradiance versus distance between source and receiver dependences in the case of 4 different radiation sources. The resonator-converter positioned at a fixed distance from receiver. Inset represents the semi-log plots of the same dependencies.

Next, we performed tests for determining EM smog from environment surrounding our measurement setup environment (this effect is inevitable). For this purpose we measured the FFT spectrum for the cases of the radiation source positioned very close to the receiver and at distance much more than 10 λ from it (the background spectrum). The results of tests conducted using an 800 W power source with a central frequency of 2.5 GHz shown in Fig. 5 (the R-C in a regime of the optical transmission) and in Fig. 6 (with the R-C in the regime of optical reflection). Here Δ*P* is an irradiance of the source minus EM smog of the surrounding received by the receiver positioned at fixed distances (given in m) from the radiation source.

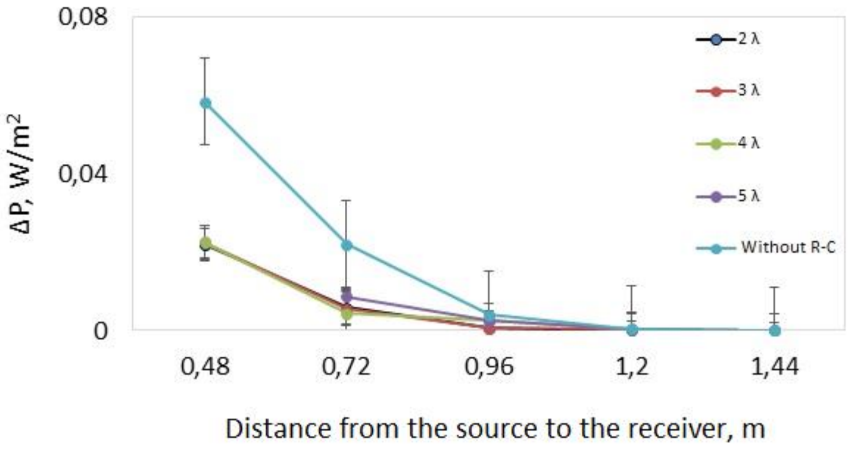

Fig. 5 The irradiance produced by the radiation source versus distance of receiver from this source dependence measured for the case of 800 W power radiation source emitting frequency band with central frequency of 2.5 GHz. The resonator-converter is in the optical transmission mode positioned at a distance of 2 - 5 λ from the receiver.

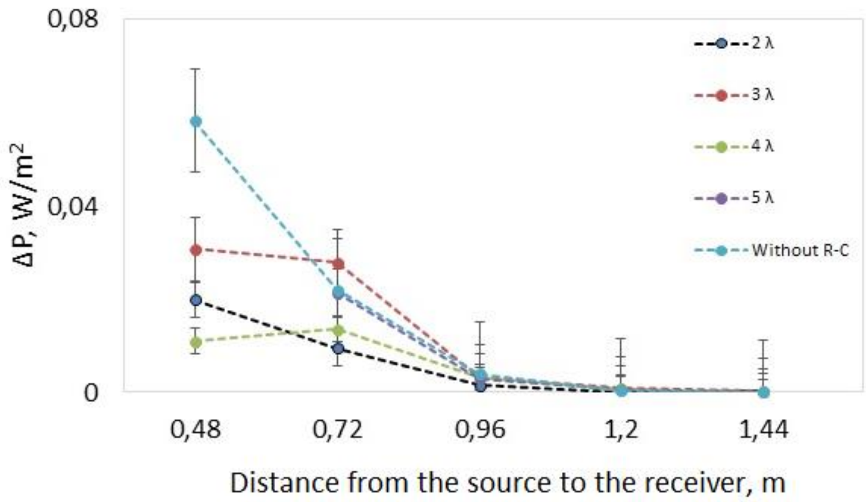

Fig. 6 The irradiance versus distance of the receiver to the radiation source (800 W, 2.5 GHz). The resonator-converter ketp at a distance of 2 - 5 λ from the receiver and used in the regime of the optical reflectance.

The efficiency of the EM smog's damping by different groups of R-Cs has been tested experimentally by means of measuring dependences of the irradiance versus distance from the radiation source, but at the same time keeping unchanged distance between the R-C and signals receiver. For this purpose we measured the electric field strength (in kV/m) versus distance (given in λ) from the source (800 W, 2.5 GHz) dependences in the case when the R-C is in the optical transmission regime ($E_{\text{R-C}}$) and in free-space (E_0) (Fig. 7 and 8).

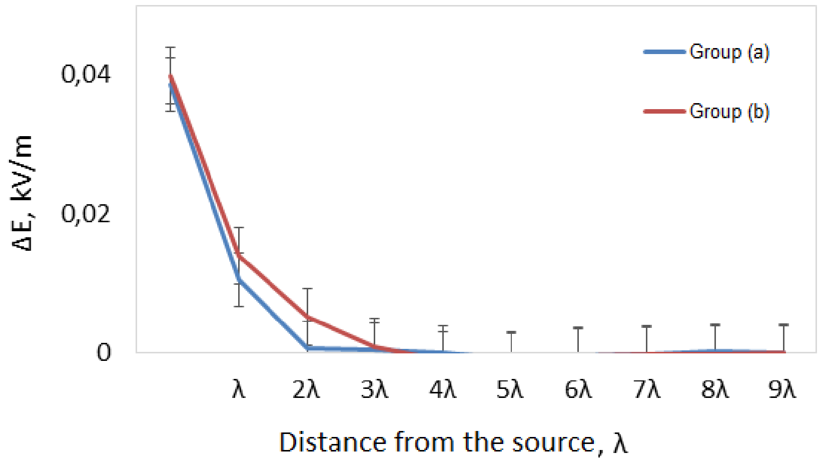

Fig. 7 The electric field strength versus the distance from the 800 W, 2.5 GHz radiation source dependences measured for two groups of R-Cs. The R-C groups operated in regime of the optical transmission.

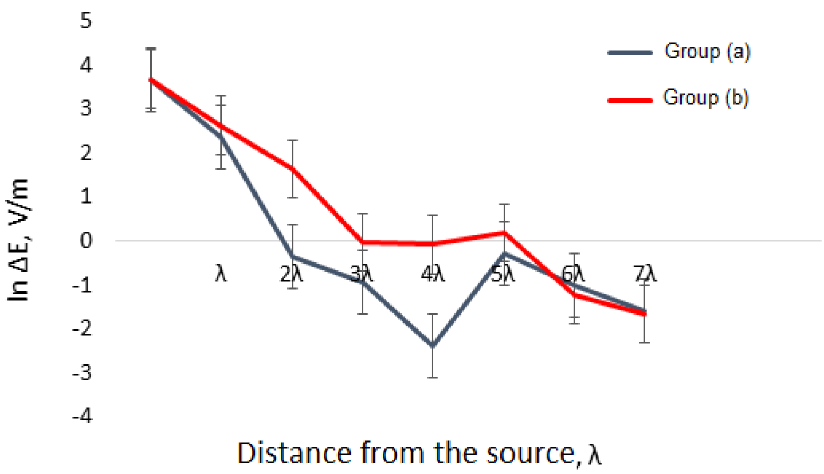

Fig. 8 A semi-log plot of the same as in Fig. 7 electric field strength versus distance to the radiation source (800 W, 2.5 GHz) dependences. The R-C groups operated in regime of the optical transmission.

Here the parameter $\Delta E = E_0 - E_{\text{R-C}}$ calculated at different distances from the radiation source. Due to incident power interaction with R-C group, the amplitude of the wave's electric field decreased on average by 25 and 22 percents for the group (a) and (b), respectively. The parameter ΔE was measured with R-C groups placed right against the radiation source. Since the signal receiver gradually moved away from the radiation source, the change of electric field strength decreased as a result of EM wave's interaction with the R-C group, until the receiver reached a distance at which the signal amplitude becomes lower than the sensitivity threshold of our measurement set up.

The electric field strength amplitude of an 800 W power source (2.5 GHz) versus the distance to the sensor dependence is shown in Figs. 9 and 10. Fig. 9 demonstrates measurements results when the R-C is in the optical transmission regime (here the R-C is positioned at a distance ranging between 2λ and 5λ (*i.e.* 24 cm - 60 cm) from the receiver) and Fig. 10 shows data when the R-C is in the regime of optical reflection.

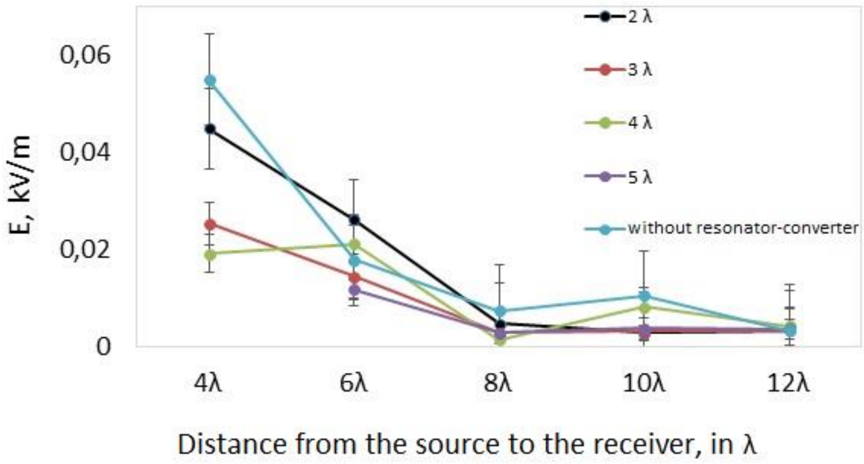

Fig. 9 The electric field strength measured by the receiver versus the distance to the radiation source, where the group of resonators-converters is in the regime of optical transmission at distance ranging between 2λ and 5λ from the receiver.

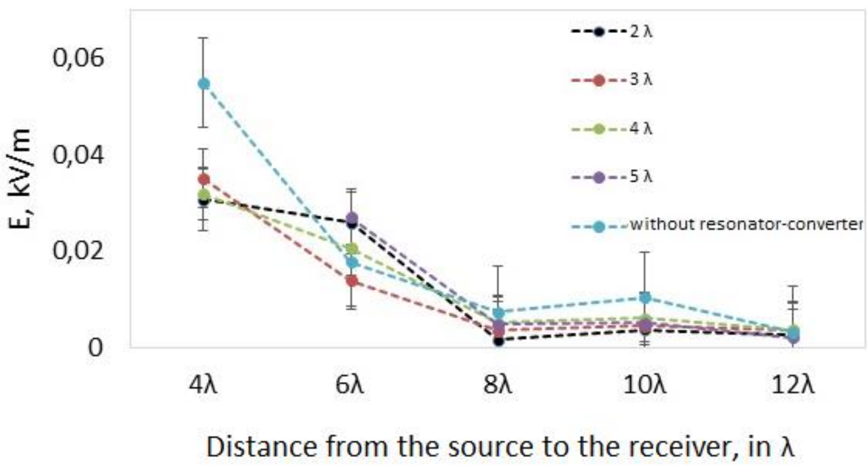

Fig. 10 The electric field strength measured by the receiver versus the distance to the radiation source, where the group of resonator-converters in the regime of optical reflection at a distance of 2λ – 5λ from the receiver.

Figs. 11 and 12 show the characteristic distances (*i.e*. signal's characteristic damping), at which, due to waves' interaction with the R-C, the electric field amplitude of an incident EM wave decreased by *e* times (*e* = 2.71828...). Characteristic damping of the signal we estimated experimentally by means of measurement of source power versus the source-R-C distance dependence, with the R-C positioned at a fixed distance from the sensor. Characteristic damping calculated for the R-C Aires Defender in the regimes of optical transmission and reflection shown in Fig. 11 and that for an R-C group (a) is shown in Fig. 12.

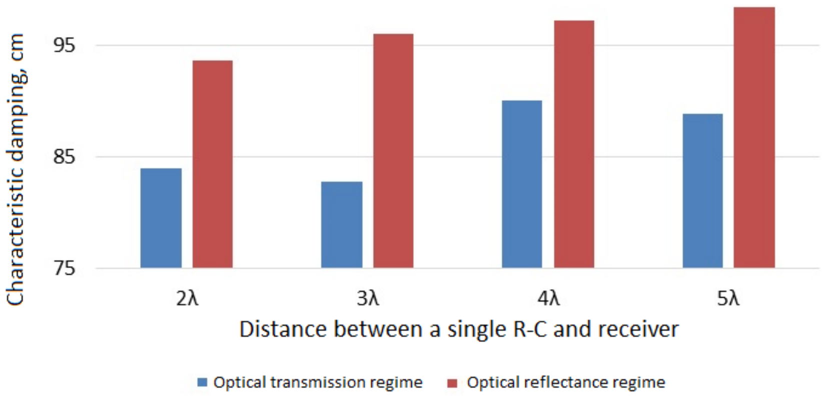

Fig. 11 The dependence of the characteristic damping versus distance (in λ) between the R-C and the signals receiver.

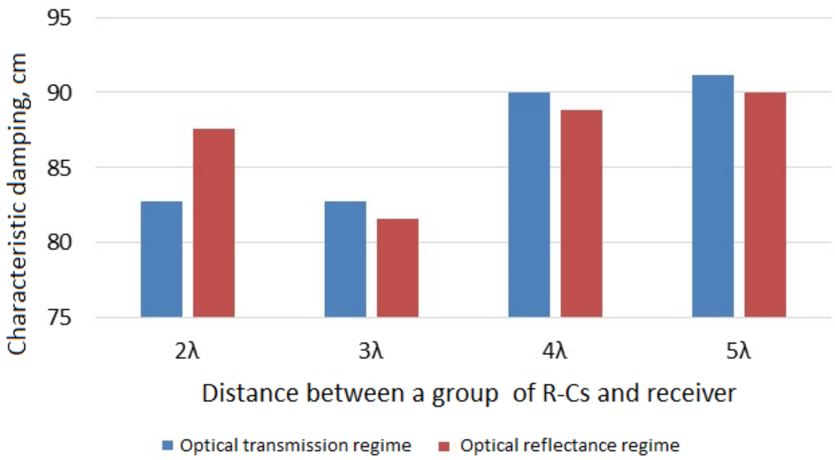

Fig. 12 The dependence of the characteristic damping of signals versus distance (in λ) between the group (a) of the R–Cs and the signals receiver.

The characteristic damping by the R-C (*i.e*. the distance of exponential decay of electric field amplitude) increases with increasing distance from the radiation source when the R-C is in regimes of optical transmission and reflection. While our tested group of R-Cs affects the difference by just a few percents when it positioned in regimes of optical transmission and reflection (in these experiments the area of group of R-Cs is of order of λ^2 and the area of each individual R-C is much lower than λ^2. Here λ is the central wavelength of the EM wave incident onto the signals' receiver). Needs mentioning that interaction of EM wave with the R-C is almost 10 percent stronger in the case if the R-C is in the regime of optical transmission (i.e. located between the radiation source and the signals receiver measuring power of an incident EM wave.

The minimum power of EM waves of 0.9 GHz frequency necessary for excitation of R-C is $E_{\text{min},0.9\ \text{GHz}}$ ~ 2 W. Considering a spherically shaped source of radiation with a surface area $S = 4\pi R^2$ (here R is the radius of this sphere), the minimum power of EM wave incident onto surface of the R-C (Aires Defender), $E_{\text{min},S}$ may be expressed as follows:

$$E_{min,S} = \frac{NS_{R-C}}{4\pi R^2}$$

here $S_{R\text{-}C}$ is the surface area of the Aires Defender R-C. According to our preliminary estimations, for the case of a 0.9 GHz central frequency EM wave the minimum incident power exciting the R-C should be equal to or higher than 490 mW.

4. CONCLUSIONS

While the R-C is located in near-field zone in respect to the radiation source, an incident EM wave with a power equal to or higher than the R-C excitation threshold creates conditions favorable for the electric breakdown inside the R-C, and the R-C excited by the incident EM wave turns into generator of ultrawide band burst of frequencies with a central frequency dependent on the characteristics of EM wave incident onto the R-C, chemical composition of the gaseous or solid environment, where the electric discharge occurs, as well as on the internal fractal structure of the R-C itself.

The characteristic damping of the EM smog by the R-C (*i.e*. the distance of *e* times decay of electric field amplitude) depends on whether the R-C is in regime of optical transmission or reflection. However, in case of wave interaction with a group of R-C, the characteristic damping is almost independent on the regimes of measurement. The interaction of an individual R-C with EM wave is stronger while the R-C is in the regime of optical transmission, *i.e.* the R-C positioned between the radiation source and the signals receiver registering the radiation emitted by the source.

According to our preliminary evaluation, minimum power of an incident EM wave with center frequency of 0.9 GHz required for excitation of the R-C itself radiation is equal to or higher than ~0.5 W. At highr excitation levels the R-C could emit EM waves of extremely broad bandwidth with a center frequency depending on characteristics of an incident EM wave, on electrical conductivity of antenna material and fineness of the internal fractal antenna structure built inside the R-C.

Further plans:

Contractual plans for Phase III:

1) A developing of a theoretical two-dimensional (2D) R-C group's model and conducting simulation of most efficient group of R-C comprising individual R-Cs of different types with optimum orientation of their surface normal in respect to direction of Poynting vector of incident EM waves and located at optimum distance one from other in a single group a) made up of two R-Cs; b) made up of 4 R-Cs and of 9 R-Cs in both cases positioning them in a parallelepiped or circle. To verify experimentally the results of simulation or theoretical calculations.
2) To develop a theoretical model of three-dimensional (3D) group of R-Cs and to conduct simulation of the most efficient group of R-Cs comprising individual R-Cs of different types with optimum orientation of surface normal in respect to the direction of Poynting vector of incident radiation and located at optimum distance one from another in the space: a) in the shape of a cube; b) in the shape of a sphere. To verify experimentally the results of simulation or theoretical calculations.
3) To evaluate the change of safe zone dimensions around the high-power radiation source, if the R-C is positioned for the regime of optical transmission and optical reflection. To calculate variation of SARs for the individual R-C and for the groups of R-Cs.
4) To simulate 2D and 3D (spatial) group of R-Cs prototype (this activity of the project we are going to do together with the manufacturer of the prototype and project partners).