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Investigation of the Circle Fractal Structure Interaction with Gigahertz Frequency Electromagnetic Waves

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Abstract

We present results of investigations of Si crystal (100) with a circularly periodic structure formed on its surface (resonator-converter) interaction with low power radiation which can be attributed to electromagnetic pollution (EP). Due EP interaction with circularly periodic (diffraction grating) structure of the front/rear antennas and periodic structure of Si crystal our device in the regime of optical reflection can efficiently damp EP if incident power is ≥ 2 W. The efficiency of EP damping by means of our device is noticeably higher than that one of measured for a regular conducting plate of identical dimensions and orientation in the space. The results of our experimental measurements and model of power attenuation by the resonator-converter is presented and discussed.

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1. Introduction

All organic and inorganic objects in nature are constantly being exposed to a natural electromagnetic radiation (EMR) produced by the cosmic radiation [1] (the biggest part of it is absorbed by the Earth atmosphere), emitted by the Earth's crust (due to nuclear reactions of radioactive elements in it), and coming from artificial sources in the highly urbanized and/or domestic industry environment. In fact, humankind, animals and plants use EMR for a variety of their living activities, like those of telecommunication, control and regulation of their various behavioral and physiological functions. However, though essential for living objects, exposure to excess low frequency (equal or higher than 50 Hz) [2, 3] and/or high frequency (below 2.5 GHz) EMR beyond the naturally evolved tolerance limits can cause various human illnesses [2] and/or harmful biological effects in humans' bodies [4, 5].

The artificial sources of ambient non-ionizing electromagnetic pollution (EP) are power supply lines (the higher the voltage, the higher radiation power), microwaves and radars, telecommunication equipment/devices and electrical appliances, radio and TV signals transmitters, even computers and their monitors, electric clocks, heated waterbeds, blankets *etc.* All together these sources create surrounding us EP with frequency of EMR ranging from 0 Hz (static electromagnetic field) to 300 GHz (microwaves and millimeter waves). The effects of extremely low-frequency EMR are dependent on dose and duration of exposure and are cumulative. Therefore, today's humankind start asking questions how to assess the exposures to the human body from EP and to protect them from excess of EMR which can lead to cells and/or neurons damage or even damage to chromosomes altering the structure of our DNA [6].

Protecting themselves from EP one can simply limit time period of direct contact with electronic appliances, but technically it is difficult to accomplish in nowadays living/working environment, be aware of high power radiation sources what is almost impossible in highly urbanized/industrial areas, or use electromagnetic shields which potentially can increase immunity of the shielded device and decreases the power of undesirable radiation from it [7]. Moreover, the electronic appliances emit power from a number of primary and secondary sources and their emissions become an uncorrelated broadband EP which can be totally suppressed only by means of the signals phasor addition for all contributions resulting the radiation field.

Our work aims on experimental testing of a silicon crystalline (100) resonator-converter interaction with low power 0.9–2.5 GHz frequency continuous wave signals which frequency can be attributed to frequency range of ambient non-ionizing EP. The resonator-converter (device) is shaped in a form of circular diffraction grating with a variable period starting with 0.001 mm wide "slits" at the device's centre and ending with 0.1 mm wide "slits" at the Si crystal edges and consists of front and rear antennas which are also circularly periodic diffraction gratings spaced by a 1-mm-thick insulator ($\epsilon = 3.5@10\text{ GHz} - 4@2.5\text{ GHz}$) [8] located in between them. Our results of experimental investigation show that the resonator-converter suppresses power of incident EMR and, due to incident wave interference with a wave reflected from device's surface, it retransforms the incident EMR in terms of frequency/wavelength and phase. Our experimental results of incident power suppression when our device is operating at room temperature in the regime of optical reflection and in the regime of optical transmission are presented and discussed.

2. Samples and measurement setup

Our tested resonator-converter (device) contains a 500- μm -thick round shaped Si (100) crystal plate glued onto surface of a front antenna (Fig. 1 *on the left*) which physical shape defined as a fourth iteration circle fractal. The surface of Si crystal plate modified by means of plasma-chemical etching of 600-nm-deep and 600-nm-wide groves which produce a net of intercrossing rings (Fig. 1 *on the right*). Since etched groves on the silicon surface affects a periodic change in crystal's thickness, the crystal behaves like a diffraction grating with a variable period produced by intercrossing rings of the fourth iteration circle fractal with a diameter of $D_1 = 7.5\text{ mm}$. It means that for every further step of iteration the diameter of rings decreases proportionally to ratio $D_2 = D_1/2$, $D_3 = D_2/2$, and $D_4 = D_3/2$ in such a way producing a diffraction grating of a variable period (Fig. 1 *on the right*).

The circles of groves on the surface of Si plate form a circularly periodic topology of the Si resonator-converter, which is fixed on a top of front antenna (Fig. 1. *on the left*). Two identical antennas, the front and rear, in our device

are used for receiving ultra-wide band frequency continuous-wave EMR with the frequency band ranging between 0.9 and 2.5 GHz frequencies, which can be attributed to frequency range of ambient non-ionizing EP. The front and rear conducting (metallic) antennas are also manufactured as diffraction gratings produced by 0.1-mm-thick and 0.1-mm-wide intercrossing rings of metal fourth iteration fractal of the circle with a diameter of $D_1 = 12.5$ mm with a diameter of rings of every further step of iteration following ratio $D_2 = D_1/2$, $D_3 = D_2/2$, and $D_4 = D_3/2$ in such a way producing a diffraction grating (Fig. 1 *on the right*) of a variable period ranging from several millimeters down to tens of micrometers.

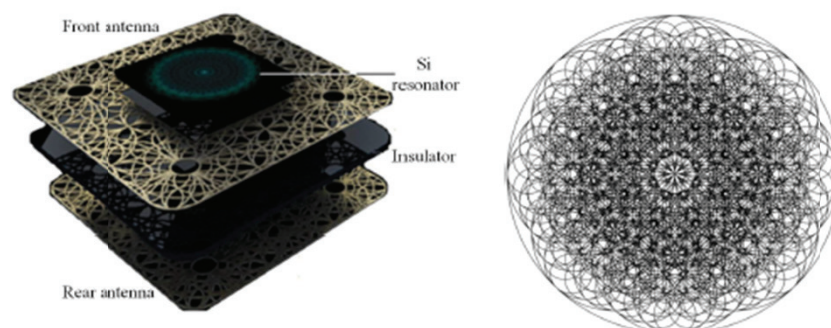


Fig. 1. Schematics of the resonator-converter consisting of a silicon resonator fixed on the top of the front antenna (*on the left*) and a schematic sketch of plasma-chemically etched grooves on its surface (*on the right*). Similar design of the fourth iteration circle fractal (*on the right*) has been applied for the front and rear antennas of this device

The equivalent circuit of the resonator-converter is a capacitor comprising two conductive electrodes separated by an insulator. The interaction of the capacitor with incident EM wave results in charging up of the capacitor C and the device's antenna gain depends of antenna impedance given by $(L_p/C)^{1/2}$ where L_p stands for the parasitic inductance of both metallic antennas and of the Si resonator.

Our measurement setup consists of continuous-wave signals generators (for this purpose we have been using different radiation sources of household appliances), emitting wide band signals in frequency band ranging between 0.9 GHz and 2.5 GHz and of resonator-converter. For signals detection we used the Signal Hound Spectrum analyzer receiving signals in the 0–8 GHz frequency band. The signals were detected in the near-field (the resonator-converter located close to radiation source) and in the far-field (the resonator-converter located at distance $L > 10\lambda$) zones. Here λ is the wavelength of the central frequency of the signal received by the signals detector.

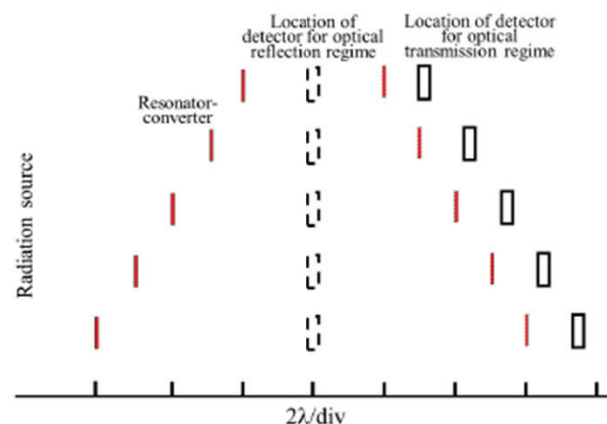


Fig. 2. A scheme explaining experimental setup for detection of signals when the resonator-converter is used in a regime of optical reflection (dashed lines) and in the regime of optical transmission (solid lines) and distances between radiation source, detector, and the resonator-converter are given in λ -as. Here λ is the wavelength of the central frequency of the source radiated wave

We measured power of 0.9–2.5 GHz electromagnetic waves (in dBm) transmitted through the resonator-converter (the regime of optical transmission (Fig. 2)) and that of reflected waves from our device (the regime of optical reflection) in the near-field and far-field zones of the resonator-converter and then the power values were converted into electric field amplitude, presuming that radiation sources are ideal electric dipoles with antenna gain of 2.15 dBi. For the optical reflection measurements, our detector of radiation we located in between radiation source and resonator-converter in the near-field and far-field zones. The power of detected signal was analyzed by means of the FFT method sampling the detected signal over a period of time and measuring amplitudes of its frequency components.

To calculate experimental mean values all measurements either under laboratory or field conditions were repeated for several times at fixed distances between the resonator-converter and the detector given in λ -as. Four different radiation sources transmitting 0.5 W @ 0.9 GHz (No. 1), 2 W @ 0.9 GHz (No. 2), 400 W @ 2.5 GHz (No. 3), and 800 W @ 2.5 GHz (No. 4) we used for our measurements. However, to minimize errors of our experimental measurements, in current report we will mainly focus on experimental results using the most powerful radiation source No. 4.

3. Measurement results and discussion

3.1. Experimental results

EMR interaction with the resonator-converter has been studied by means of detection of residual signal power versus distance between the detector and a radiation source in the case when the resonator-converter operates in the regime of optical transmission. Figure 3 represents difference in electric field amplitudes $E_0 - E_1$ versus distance of the detector from mentioned above four types of radiation sources. Here E_0 stands for electric field amplitude of radiation source emitted signal and E_1 is the residual electric field amplitude transmitted through the resonator-converter which was located in the near-field zone of radiation source.

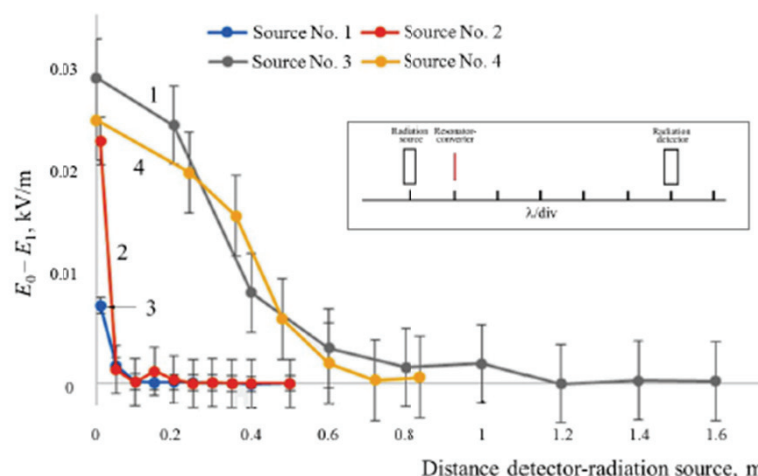


Fig. 3. A plot of difference of electric field amplitudes ($E_0 - E_1$) recorded by the signals detector versus distance detector-radiation source. Here E_0 is electric field amplitude of the source emitted signal and E_1 is electric field amplitude of the signal transmitted through the resonator-converter which was fixed in the near-field zone of the radiation source. Numbers and colors of curves in the graph represent results of experimental measurements using four different sources of EMR. Inset represents a schematic of our measurement setup

The electric field amplitude of the transmitted through the resonator-converter gigahertz frequency EMR decreased by ~27 % (i.e. electric field amplitude damping ratio -2.07 dB) level on average in whole range of our tested distances from the radiation source No. 4 (Fig. 3, curve 1 (grey)). Here and in all other experimental cases the resonator-converter is attached directly to the frame of a radiation source, i.e. located in its near-field zone.

Increasing distance from the radiation source, the parameter E_0-E_1 gradually decreased and finally vanished at distance 1.2 m (curve 1), 0.85 m (curve 4) and at distances below 0.2 m (curves 2 and 3).

All curves in Figure 3 show strongly nonlinear behavior with increasing detector's distance from the radiation source and this feature let us to predict that the lever of power damping by the resonator-converter should depend on power of incident EMR. Since our tested radiation, sources are not zero-dimensional and in all cases amplitude and frequency range of radiation is a result of superposition of radiation of several primary and secondary sources, the electric field amplitude of 800 W radiation source does not decrease with increasing distance squared. However, the variation of the parameter E_0-E_1 show that the resonator-converter turns-on at high power and turns-off when the incident power appears to be below some threshold value $P_{\min}$. As it follows from our measurement results the minimum power required for turning-on the resonator-converter is of order of $P_{\min} \sim 2$ W (curve 2 (red)). Our preliminary results also show that $P_{\min}$ is a function of frequency/wavelength of an incident electromagnetic wave and $P_{\min}$ decreasing with increasing central frequency of an incident EMR.

The electric field amplitude of 800 W power radiation source versus distance to the signals detector is shown in Fig 4 on the left (here the resonator-converter used in the regime of optical transmission) and in Figure 4 on the right (the regime of optical reflection). In both experimental cases, the distance between the resonator-converter and signals detector was kept constant while the detector moves away from the radiation source.

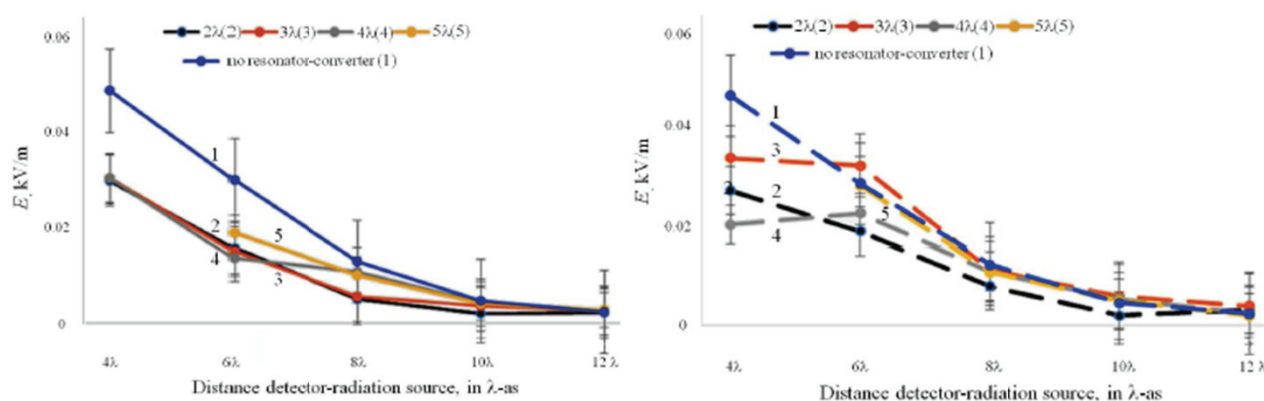


Fig. 4. The electric field strength detected at various distances (in λ -as) from an 800 W radiation source. Here figure (on the left) represents the case when our tested resonator-converter used in the regime of optical transmission and figure (on the right) when the resonator-converter used in the regime of optical reflection. In both experimental cases the distance between the resonator-converter and detector is fixed at 2λ (curve No. 2), $3\lambda(3)$, $4\lambda(4)$, and $5\lambda(5)$ (see figure legends) while the detector moves away from the radiation source. Here $\lambda = 12$ cm is the wavelength of the central frequency of the source radiated signals

The electric field amplitude of the transmitted through the resonator-converter EMR decreases considerably (Fig. 4 on the left), however the parameter E_0-E_1 (it was calculated by subtracting curves Nos. 2-5 from curve No. 1 in figure) does not depend on the resonator-converter distance from the detector. Slightly weaker damping of the electric field amplitude, but very similar behavior of the parameter E_0-E_1 with increasing distance from the detector demonstrates the conductive (metallic) plate when we substituted it for the resonator converter. Having same dimensions as the resonator-converter the metallic plate in our measurement setup exhibited effect of electromagnetic screening of EMR electric field component demonstrating 7–8 percent lower level of EMR damping if compare it with that one of the resonator-converter.

When the resonator-converter operated in the regime of optical reflection (Fig. 4 on the right), the maximal damping of electric field amplitude we observed for the distances between the resonator-converter and the detector lower or equal to 2λ or when the resonator-converter attached to the frame of the detector. These results let us to conclude that most efficient damping of the EP could be expected when the resonator-converter operates in regime of the optical reflection and when incident EMR power is greater or equal to $P_{\min}$.

3.2. Results of numerical simulation

Our results of numerical simulation of the resonator-converter interaction with an incident monochromatic wave of 550 THz frequency showed that 5.75 cm in diameter and 1 mm thick Si crystal modified surface by means of plasma-chemically etched 0.5- μm -wide and 0.5- μm -deep grooves undergoes non-uniform distribution of free carriers. An incident EMR charges up Si crystal producing stronger electric field (*i.e.* inducing larger concentration of free carriers) between the bottom of grooves located on a top of the silicon crystal and crystal's bottom surfaces. We simulated both the redistribution free-carrier concentration along the Si crystal surface and a strength of the electric field in the near-field zone of this crystal. Our results showed that high concentration of free-carriers collected in the grooves of the Si crystal can initiate a spontaneous electric discharge causing the electric field strength redistribution and flow of electric current along the resonator-converter surface [9]. It means that for the most efficient damping of EP of specific frequency range the doping of Si crystal (*i.e.* its electric conductivity) of the resonator-converter has to be optimized. It is also demonstrated that efficiency of the EMR damping by the resonator-converter is a function of Si crystal and metallic antennas topology as well as characteristic frequency/wavelength of an incident EMR.

Due to EMR interaction with both antennas and signals interaction with diffraction grating built on the surface of Si crystal, the signal is back scattered in a form of coherent radiation with the maximal amplitude of the electric field located in the centre of the Si crystal (Fig. 5).

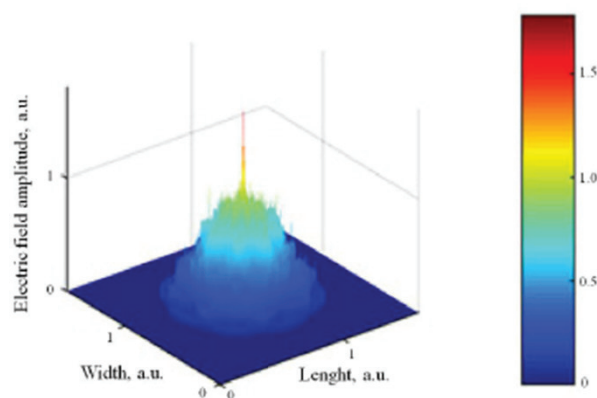


Fig. 5. The three-dimensional (3D) view of the electric field strength distribution in near-field zone of the 1 mm thick, round (5.75 cm in diameter) shaped Si crystal with plasma-chemically etched 0.5- μm -wide and 0.5- μm -deep grooves of rectangular cross-section on its surface

Increasing power of an incident EMR, a noticeable field amplitude appears also at the crystal edges in such a way producing a bell-like shape of field distribution in the near-field zone of the resonator-converter. The backscattered EMR interfere with incident EMR and the electric field distribution around the resonator-converter surface turns into an intricate three-dimensional (3D) structure [9]. A backscattered signal affects redistribution of electric field amplitude recorded by the signals detected, exhibiting sharp non-linear growth of electric field amplitude starting with the device's antenna edges and spreading towards its center as well as towards the centre of the Si crystal. Our results of numeric simulation show that due to backscattered wave interference with incident EMR, the frequency of resulting wave could increase for several times and for our tested geometry of Si crystal it increases by 3.2 times [9] in respect to 550 THz frequency of monochromatic EMR from the radiation source.

Conclusions

The resonator-converter partly suppresses power of incident on it electromagnetic radiation (EMR). The maximal efficiency of signals suppression can be achieved when the resonator-converter is attached directly on a frame or

located in a near-field zone of the radiation source, since in the near-field zone is easier to reach and exceed the threshold power $P_{\min}$ necessary for the device's onset.

The minimal power needed for the resonator-converter's excitation is $P_{\min} \geq 2$ W measured for the 2.5 GHz frequency radiation source. Our preliminary results also suggest that $P_{\min}$ is a function of antenna and Si crystal surface topology, doping of the Si crystal, and frequency/wavelength of an incident EMR.

For the case of damping of electromagnetic pollution (EP) (i.e. far-field zone of a radiation source), the maximal damping of EMR power we achieved when the resonator-converter is directly attached to the frame of the signals detector or located at distance shorter or equal to 2λ away from it. Therefore, as a potential protector against EP, the resonator-converter should be used in the near-field zone of signals detector (i.e. human body, shielding electronic device etc.) and/or radiation source (i.e. source of potential EP).

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