# INVESTIGATIONS OF A PHOTOVOLTAIC POWER GENERATOR IN AN ELECTROMAGNETIC AMBIENCE

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ABSTRACT: We have investigated the reaction of photovoltaic cells to external electromagnetic fields in a frequency range of 10 Hz to 1 GHz. Outdoor recordings of received RF noise from the ambient were sampled for different solar cells and modules and compared with the reception of a simple whip antenna which represents a monopole for electromagnetic fields. Additionally in the laboratory well defined signals were generated and their reception was investigated depending on geometrical factors of the cells, such as orientation, size and distance. Cells, partly processed silicon wafers and patch antennas of equivalent dimensions were investigated. Two antenna models, namely dipole and patch configuration, are compared with the experimental findings. It was found that the gain in the investigated frequency range increases essentially linear with the cell area similar to patch antennas. A crystalline silicon cell of 100 $cm^2$ has almost the same signal amplification as an 83 cm long whip antenna remaining coarsely constant over the whole frequency range. For narrow frequency bands however the signal attenuation or amplification is strongly modified by the dipole behavior caused by the front metal grid.
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## 1 INTRODUCTION

Rising interest and increasing subsidies in the last years led to an exponential increase in the installed capacity of photovoltaic power generators. Numerous solar parks are already in operation under construction or are planned in the European Union, which cover areas of several thousand square meters. The adaptation of solar modules for building integration results in large facades covered with interconnected electronic devices. It can be said that photovoltaic power generators with an active area of over 1000 m² are no rarity anymore.

Considering the huge area covered with electronic devices with a complex AC behavior, which is not fully investigated yet, a reaction to external electromagnetic fields can be expected. Given the interaction of the solar modules with power electronics and the power grid, yet unknown problems of electromagnetic compliance may arise. [1-3]

Several possible mechanisms of the interaction between photovoltaic modules and electromagnetic fields or radiation have to be taken into account: radiation may be received or reflected by the semiconducting devices, or may be conducted to the subsequent power conditioning electronics. In opposite direction system distortion can be emitted to air by solar modules. Different ambient sources, such as vibrations, light fluctuations or internal noise [4], can additionally generate AC currents in the photovoltaic power plant thus increasing the total electric noise level in the system.

The goal of our present work is a qualitative understanding of the reaction of photovoltaic cells to external electromagnetic fields. Different cells were investigated in a frequency range of 10 Hz to 1 GHz which covers a great portion of today's electromagnetic emission sources. The influence of various solar cell design parameters like front metal grid and cell dimensions were examined.

## 2 THEORY

The general layout of most solar cells and modules suggests using two antenna models for the theoretical description of solar cells as a receiver or emitter of RF radiation.

The first approach assumes that the front grid of the currently most widespread c-Si cells can be modeled by an array of dipoles. The dipoles given by the highly conductive grid are electrically isolated from the back contact. The insulator is determined by the dielectric properties of the semiconductor and the cell's thickness. In this model the back contact simply acts as a reflector for the electromagnetic wave. Since the ideally negligible dielectric losses between front and back contact are essential for the application of this model only thick semiconducting layers present only in crystalline silicon cells will sufficiently well match the condition of good electrical isolation. [5] Depending on the geometry and number of dipoles one or multiple band-pass frequencies can occur. For a single dipole the impedance can be found using well known equations [5]. For interconnected, multiple dipoles an array factor modifying the radiation pattern of the single dipole can be found for simple geometrical configurations. For example for the H-pattern front grid with 2N fingers at a distance D, the array factor AF in spherical coordinates is:

$$AF_{total} = \frac{\sin\left(2kd\cos\theta\right)}{2\sin\left(kd\cos\theta\right)}\frac{\sin\left(\frac{N}{2}kD\left(\sin\theta\cos\phi+1\right)\right)}{N\sin\left(\frac{1}{2}kD\left(\sin\theta\cos\phi+1\right)\right)}$$

where k is the wavenumber.

In the second approach the front contact is assumed to form an electrically homogenous area – the patch – separated from the reference or ground potential assigned to the back contact. In this case the dielectric in between need not be assumed lossless and can be described by an effective permittivity (dielectric constant) which generally is complex. For model calculations most often the imaginary part however is neglected. Thus the reception properties depend on the dimensions of the cell and the effective permittivity of the substrate. This model may give a good representation of thin film cells. [6] The transfer function typically has only one very broadband band-pass characteristics. The resonance frequency, $\nu_{res}$, can be roughly estimated using the simple transfer line model, which gives:

$$L_{eff} \cdot \nu_{res} = \frac{c}{2\sqrt{\epsilon_{eff}}}$$

Where $c$ is the velocity of light. The effective length $L_{eff}$ and the effective permittivity $\varepsilon_{eff}$ can be calculated using empirical formulae for example given in [6].

## 3 EXPERIMENTAL

### 2.1 Set Up

In the laboratory a well defined signal (by means of amplitude, frequency and phase) was emitted by a dipole antenna and the received signal was analyzed at the samples terminals. The setup for the performed experiments consists of a lock-in amplifier with a built-in sine wave generator, a signal generator, a dipole antenna and the devices under test (DUT). The sending antenna was mounted onto the pen holder of a plotter in order to vary the position between sender and receiver.

In order to take advantage of the high sensitivity of the lock-in amplifier detection with an upper frequency limit of 100 kHz, two different operation modes were used:

Below 100 kHz, the emitted sinusoidal signal is directly generated by the signal generator with which the lock-in amplifier synchronizes.

For higher frequencies the internal generator of the lock in amplifier is used to produce a modulation signal around 1 kHz. The external function generator produces a carrier signal which is amplitude modulated by the lock in amplifier's output. This mode is used for frequencies up to 20 MHz.

Antenna and DUT are placed in an electromagnetically shielded compartment, which has the size of 60×51×45 cm³. The shielding is achieved by the use of grounded 1 mm steel plates.

In the "natural" electromagnetic ambience given by the numerous RF emitting sources, indoors as well as outdoors, the input of a 83 cm long whip antenna (resonance frequency approximately 200 MHz) was simultaneously recorded with the input of different solar cells and panels using a 2 $GSs^{-1}$ sampling oscilloscope. Both devices, antenna and solar cell, were connected via a 1 m long coaxial transmission cable to the high impedance input of the oscilloscope without a matching circuit. The time domain signals were Fourier transformed and the ratio of the squared amplitudes up to 1 GHz was averaged over the time. Since only "natural" sources were received several gaps in the frequency range occurred were the signal levels remains permanently close or below the measurement resolution of 80 µV. In these cases the derived ratio leads to large deviations.

## 4 RESULTS AND DISCUSSION

### 4.1 Sender-Receiver Geometry

Several cells were examined in different orientations towards the sending antenna. If the antenna length is parallel to the x-axis, the directions were the following:

- cell in plane with the sending antenna (in the x-y-plane)
- cell in the x-y-plane, rotated by 90°
- cell in the x-z-plane
- cell in the y-z-plane

The cell in plane with the sending antenna, with its fingers aligned with the dipole axis (in the following referred to as parallel alignment), responded strongest to the external field at low frequencies. The cell in the x-z-plane, which is also in parallel alignment, showed the second best gain, while the other two configurations showed a 12 dB weaker reaction. Contrary to the findings of Wada et al. [1], who assumed the bus bars to give the major contribution and ignored the finger influence, in this case the alignment of the fingers parallel to the dipole leads to higher amplitudes than the parallel alignment of the bus bars.

### 4.2 Size Dependency

Comparison between a monopole antenna and differently sized crystalline silicon solar cells shows that the gain increases linearly with the area of a cell. Figure 1 shows the gain per area for four DUTs, which is very similar for three of them at low frequencies. Only the gain of the DUT drawn in red is approximately 3 dB weaker. In contrast to the rectangular shape of the other cells this cell has a circular shape which could potentially explain the weaker amplification. At frequencies above 10 kHz differences between the cells virtually increase most likely due to the lack of strong signals, the tendency however remains similar.

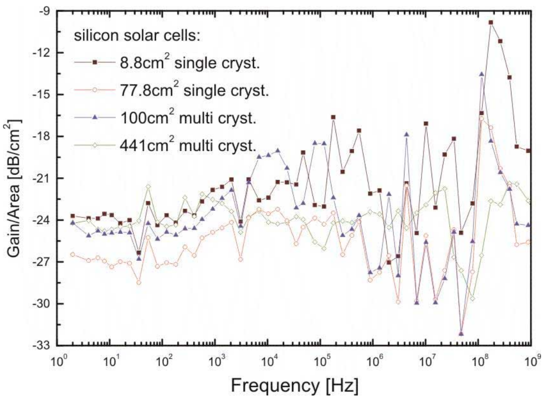


**Figure 1:** gain per area for four solar cells

The difference between two samples whose measured signal intensity differed by a factor of two could be explained comparing their dipole line density. The DUT with the higher intensity had a twice as narrow front grid as the DUT with the weaker signal. Roughly a c-Si cell with an area somewhat larger than 100 $cm^2$ will reach at least zero gain compared to the simple whip antenna throughout the whole frequency range.

4.3 Comparison with Patch

The signals received by a 8.8 cm² and a 100 cm² sized crystalline solar cell were compared with equally sized patches of copper covered hard paper.

As can be seen in figure 2, the measured gains differ very little below 2 MHz. Above this value the smaller cell shows more similarities with the patch than the bigger cell. The theoretical resonance frequency for the 100 cm² patch is ~450 MHz, for the 8.8 cm² patch 1.35 GHz, while measurements went up to 20 MHz.

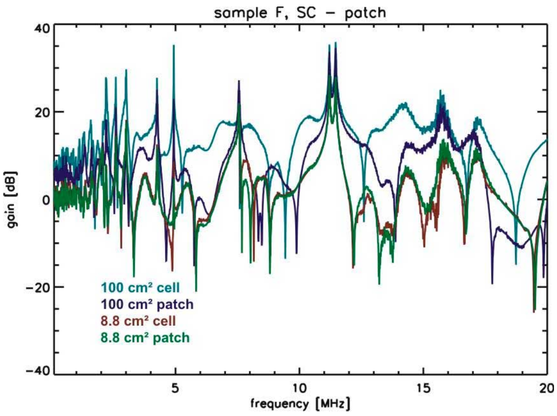


**Figure 2:** Comparison of c-Si solar cells with equally sized patches

4.4 Comparison between c-Si and a-Si

Comparing the signal reception of an amorphous silicon mini module with those of a crystalline silicon module showed that a-Si cells amplify electromagnetic radiation better than c-Si devices. As can be seen in figure 3, the gain of the amorphous module is at least 6 dB higher than that of the crystalline module, although its area is less than 1/3 of the c-Si module.

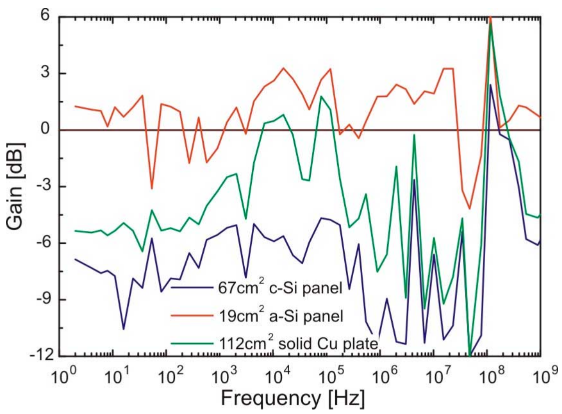


**Figure 3:** Gain of a crystalline and an amorphous silicon solar panel, as well as a solid copper plate for comparison.

5 CONCLUSIONS

Our measurements showed that, for crystalline silicon cells, the reception of electromagnetic radiation depends linearly on the cell area, at least at low frequencies (below 10 MHz). The front grid can have significant influence depending on the line density. Comparison with a metal patch showed very good agreement for a small cell (<10cm $^2$) and a fair agreement for a 100 cm² cell.

This leads to the conclusion that the patch antenna model may only be used to roughly describe the reception behavior of crystalline silicon solar cells. This is likely due to the fact, that the front side is covered by a conductive grid rather than by a homogenous patch. Corrections following a dipole model have to be applied to include the front grid influence.

Generally thin a-Si film cells amplify RF signals and hence EM noise better than crystalline silicon cells. Their structure strongly resembles that of microstrip patch antennas, because of its similarities: a dielectric substrate (eg. a-Si) is bounded by two conductive plates (the front and back contacts). Accordingly, their behavior may be described using a patch antenna model only which accounts for the lossy dielectric.

For practical applications it should be noted that the 19 cm² a-Si panel received more noise than the 83 cm reference dipole. Given a photovoltaic power generator with an output of 1 kWp a 500 times higher gain may be expected leading to significant output power distortion at the terminals of the photovoltaic assembly. From here it will be lead to the input of the power conditioning unit. Although it could be expected that attenuation takes place with increasing cable length no appropriate guidelines or regulations presently exist for that part of a photovoltaic power generator.

Following the reciprocity theorem, a solar cell array may also emit significant amounts of undesired electromagnetic radiation if it is excited by unfiltered noise in the power electronics, light fluctuations or vibrations.

The radiation or absorption in certain frequency bands may cause severe EMC issues. Depending on the size of single cells technical appliances i.e. for mobile communication, GPS or WLAN may be jammed.

In figure 3 an increased gain can be seen around the range from 30-300 MHz. This range should be paid additional attention since biological systems show increased reaction to electromagnetic radiation in this frequency domain.

Considering the rising interest concerning exposure of the human body to electromagnetic radiation and the increase in installed photovoltaic power generators, this field of research requires additional attention.

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