



universität
wien

DIPLOMARBEIT

Titel der Diplomarbeit

The Reaction of Photovoltaic Power Generators
to External Electromagnetic Fields

angestrebter akademischer Grad

Magister/Magistra der Naturwissenschaften (Mag. rer.nat.)

Verfasserin / Verfasser:	Markus Drapalik
Matrikel-Nummer:	0308992
Studienrichtung (lt. Studienblatt):	A 411 Diplomstudium Physik
Betreuerin / Betreuer:	Wolfgang Lang

Wien, am 06.12.2009

Contents

1. Motivation	1
2. Theory	3
2.1. Antenna Fundamentals	3
2.1.1. Reciprocity Theorem	4
2.1.2. Current Distribution	4
2.1.3. Impedance	4
2.1.4. Radiation Pattern	5
2.1.5. Gain	6
2.1.6. Hertz Dipole	6
2.1.7. Antenna Arrays	7
2.2. Theory of Dipole Antennas	7
2.2.1. Infinite / Small Dipole	8
2.2.2. Finite Dipole	9
2.3. Theory of Patch Antennas	9
2.3.1. Transmission Line Model	10
2.3.2. Cavity Model	11
2.4. Photovoltaic Power Generators	12
2.4.1. Working Principle	13
2.4.2. Parts of a Solar Cell	13
2.4.2.1. Substrate	13
2.4.2.2. pn-Junction	14
2.4.2.3. Front Grid	14
2.4.2.4. Back Metallization	15
2.4.3. Thin Film Cells	15
2.5. Comparison Solar Cell - Antenna	16
2.5.1. Comparison with Dipole Antenna	16
2.5.1.1. single dipole array	16
2.5.1.2. double dipole array	18
2.5.2. Comparison with Patch Antenna	23
2.5.2.1. Single Patch	23
2.5.2.2. Two Patches	24
3. Setup	27
3.1. Function Generator	28
3.2. Lock-In-Amplifier	28

Contents

3.3. Sending Antenna	30
3.4. Restrictions	32
3.5. Data Evaluation	32
3.5.1. Comparison with Sender	33
3.5.2. Comparison with Receiver	34
4. Samples	35
4.1. Laboratory Cells	35
4.2. Industrial Cell	37
4.3. aSi Thin Film Cell	38
4.4. Front-to-Back Contacted Cell	38
5. Experimental Results	39
5.1. Sender-Receiver Geometry	40
5.2. Distance Dependence	43
5.3. Size Influence	45
5.4. pn-Junction Influence	47
5.5. Back Metallization	48
5.6. High Frequency Range	49
5.7. Comparison with Patch	50
6. Conclusions	53
Bibliography	55
A. Addendum	57
A.1. Symbols	57
A.2. Constants	58
B. curriculum vitae	59
C. Abstract - English	61
D. Abstract - German	63

Acknowledgement

My special thanks go to Ass. Prof. Viktor Schlosser, who suggested this diploma thesis. His support and advice in the laboratory as well as in writing made this work possible.

Further thanks go to Claudia and Gilbert Disanto who helped with phrasing and in reading proof.

I further want to acknowledge my friends and relatives who supported throughout the time of writing this thesis.

Citing herself, I want to thank my mother for fulfilling her obligation to facilitate my studies.

Finally a big thank-you goes to my fiancée who endured the ups and downs of my work while working on her own thesis.

1. Motivation

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 have been installed and are planned in the European Union. These consist of multiple solar trackers on which several square meters of solar modules are mounted. The development of solar cells and modules adapted for building integrated photovoltaics (BIPV), which includes cells with anti-reflection coating in various colors and semi-transparent cells that can replace windows glass, results in large areas covered with interconnected solar modules. It can be said that photovoltaic power generators with an active area of over 1000 m^2 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 electronic and the power grid, yet unknown problems of electromagnetic compliance may arise.

Various possible mechanisms of interaction with electromagnetic fields or radiation have to be taken into account: radiation may be absorbed or reflected, or may pass through the cell. Different sources, such as vibrations or light fluctuations¹, can generate AC currents in the photovoltaic power generator, which may likewise cause emission of radiation from the system.

The goal of this diploma thesis is a qualitative look at the reaction of photovoltaic cells to external electromagnetic fields of low frequency. Different cells were investigated in a frequency range of 10 Hz to 20 MHz and various design parameters like front grid and size influence are discussed.

¹These are research targets of other diploma thesis being written in our research group.

1. Motivation

2. Theory

In the following, fundamental theory of antennas and of photovoltaic power generation will be summarized. Additionally, two forms of antennas will be discussed in more detail: the dipole antenna and the patch antenna. Finally, the restrictions of describing the behavior of solar cells in an electromagnetic environment with the introduced antenna models will be shown.

2.1. Antenna Fundamentals

The basic function of antennas is to transform electromagnetic energy into radiative energy and vice versa. Accordingly, two aspects of an antenna have to be considered: firstly, it is part of an electric circuit and has properties such as the impedance, which describes the relation between voltage and current in the circuit; secondly, it is a radiating element and has characteristics like directivity or gain. Most properties of practical interest can be evaluated from the radiation pattern and the impedance of an antenna, which again can be derived from the current distribution on the surface and in the volume of an antenna.

Considering that the radiation patterns of simple antennas usually have cylindrical or spherical symmetry, in the following spherical coordinates will be used. As illustrated in figure 2.1, r denotes the radial distance of a point P from the origin, θ the inclination from zenith direction and ϕ the azimuth, which is the “angle between the reference direction on the chosen plane and the line from the origin to the projection of P on the plane” [Wikipedia, 2009].

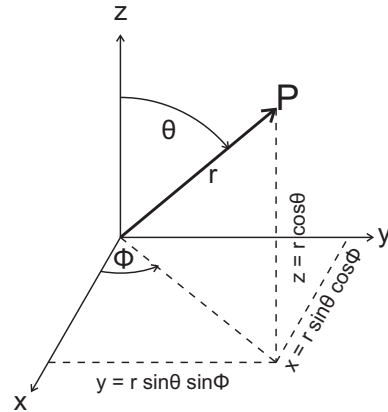


Figure 2.1.
relation between Cartesian and
spherical coordinate system
(after Tipler [2000, p. 1267])

2. Theory

2.1.1. Reciprocity Theorem

Being aware that an antenna can either be used to send or receive electromagnetic radiation, the differences between these two cases have to be discussed.

The key properties of an antenna, the impedance Z_A and the radiation pattern ψ , are given by the current distribution (and eventually the polarization current). While in the sending case the current distribution is determined mostly by electronic circuit connected to, the frequency of the applied voltage and the geometry of the antenna, in the receiving case the current distribution depends on the incident angle and polarization of the incoming wave.

The reciprocity theorem states that given an antenna made of electrically isotropic materials

- the antenna impedance is identical when transmitting and when receiving
- the radiation pattern of the antenna in the transmitting case is identical with the one in the receiving case. [Chang, 2003, p. 493]

Accordingly, it is sufficient to analyze an antenna for one of the two cases. As it is easier to find mathematical models for transmission, the properties discussed in the following sections will be described for a sending antenna.

2.1.2. Current Distribution

All properties of an antenna can theoretically be derived, if the current distribution, which is the distribution of the current on the surface and in the volume of an antenna, is known. Thus, finding the current distribution is the basis and most often the major difficulty of antenna theory.

For ideal antennas with a simple geometry closed form solutions can be found, which can be corrected with empiric findings if necessary. For more complex antennas, computer assisted models are required, of which many have been developed. These are usually based on the method of momentums for small antennas (up to few wavelengths), or on GTD (general theory of diffraction) approaches for bigger antennas and antenna arrays [Chang, 2003].

2.1.3. Impedance

The impedance of an arbitrary metallic antenna, of which the current distribution is known, can be found with the following formula:

$$Z_A = \frac{i\omega\mu_0}{4\pi} \iint_S \iint_S \left[\frac{\mathbf{j}(\mathbf{r}_s) \cdot \mathbf{j}(\mathbf{r}'_s)}{I^2} - \frac{1}{k^2} \frac{q(\mathbf{r}_s) q(\mathbf{r}'_s)}{Q^2} \right] \frac{e^{-ikr_{ss'}}}{r_{ss'}} dS dS' \quad (2.1)$$

with

$$\begin{aligned} r_{ss'} &= |r_s - r'_s| \\ S &= S_M + S_T \\ q(r_s) &= -\frac{1}{i\omega} \nabla_s \cdot \mathbf{j}(r_s) \\ k &= \frac{2\pi}{\lambda_0} \end{aligned}$$

where $\mathbf{j}(r_s)$ is the current distribution and $q(r_s)$ the charge distribution, while I is the input current and $Q = \frac{I}{i\omega}$ the electrical charge at the antenna port. The integration surface S consists of the metal surface S_M of the antenna and the port surface S_T . k is the free space wavenumber, which may also be expressed as $k = \omega\sqrt{\epsilon_0\mu_0}$. [Chang, 2003, p. 490f]

So, if the current distribution is known to an acceptable degree, it is possible to calculate the input impedance of an antenna. Due to the complexity of antenna design, in many practical cases it is easier to use empirical data.

2.1.4. Radiation Pattern

“The radiation pattern of an antenna is defined by the electric field distribution which the antenna generates on a sphere of large radius r centered about the antenna.” [Chang, 2003, p. 491]

Far away from the antenna, the electromagnetic field does not change anymore with r , except for the propagation factor e^{-ikr}/r . So the relationship between the radiation pattern ψ and the electric field $\mathbf{E}$ can be defined as:

$$\mathbf{E}(r, \theta, \phi) = \frac{e^{-ikr}}{r} \psi(\theta, \phi) \quad (2.2)$$

As stated above, the radiation pattern can be derived from the current distribution as well:

$$\psi = \frac{ik}{4\pi} \sqrt{\frac{\mu_0}{\epsilon_0}} \hat{\mathbf{r}} \times \left\{ \hat{\mathbf{r}} \times \left[\iint_{S_M} \mathbf{j}(r_s) e^{ik\hat{\mathbf{r}} \cdot \mathbf{r}_s} dS + i\omega \iiint_{V_D} \mathbf{p}(r_v) e^{ik\hat{\mathbf{r}} \cdot \mathbf{r}_v} dV \right] \right\} \quad (2.3)$$

where $\hat{\mathbf{r}}$ is the unity vector and $i\omega\mathbf{p}(r_v)$ is the polarization current in the dielectric regions of the antenna volume V_D .

The power radiation pattern, which describes the normalized magnitude of the poynting vector at a given point, can be derived from the above field strength radiation pattern by:

$$G(\theta, \phi) = \frac{4\pi r^2 |\mathbf{E} \times \mathbf{H}|}{P_{rad}} = \frac{4\pi |\psi|^2}{\int_0^{2\pi} \int_0^\pi |\psi|^2 d\theta d\phi} \quad (2.4)$$

2. Theory

where $\frac{P_{rad}}{4\pi r^2}$ is the power of an isotropic radiator with the same total radiated power, which is used as normalization factor. Since the power radiation pattern describes the radiated power compared to an isotropic radiator it is dimensionless.

2.1.5. Gain

The maximum of the radiation pattern of an antenna defines the main beam direction and determines its directivity gain G_D by comparison with an isotropic radiator with the same input power. If the normalized power radiation pattern (equation 2.4) is used, the directivity gain is identical with its maximum. For practical reasons, it is usually denoted in decibels:

$$G_D = 10 \cdot \log G_{max} \quad (2.5)$$

If the antenna losses are considered, the antenna gain G_A can be found:

$$G_A = 10 \cdot \log G_D - 10 \cdot \log L_A \quad (2.6)$$

where the loss factor L_A is the ratio of the antenna input power to its radiated power. For real antennas, this factor is always bigger than one, for good antennas close to one.

2.1.6. Hertz Dipole

The Hertz dipole is an ideal dipole antenna, e.g. an infinitely small dipole with finite dipole moment $\mathbf{p} = (0, 0, p)$. Assuming the dipole moment is located at origin and aligned with the z-axis, it radiates a field which is given by [Chang, 2003, p. 499f]

$$\begin{aligned} E_r &= -\frac{\omega p}{4\pi} \sqrt{\frac{\mu_0}{\epsilon_0}} k^2 \left(\frac{2}{(ikr)^2} + \frac{2}{(ikr)^3} \right) e^{-ikr} \cos \theta \\ E_\theta &= -\frac{\omega p}{4\pi} \sqrt{\frac{\mu_0}{\epsilon_0}} k^2 \left(\frac{1}{ikr} + \frac{1}{(ikr)^2} + \frac{1}{(ikr)^3} \right) e^{-ikr} \sin \theta \\ H_\phi &= -\frac{\omega p}{4\pi} k^2 \left(\frac{1}{ikr} + \frac{1}{(ikr)^2} \right) e^{-ikr} \sin \theta \end{aligned} \quad (2.7)$$

in spherical coordinates. At sufficiently far distance, higher order terms in $1/r$ are negligible, thus E_r becomes zero and E_θ reduces to

$$E_\theta = \sqrt{\frac{\mu_0}{\epsilon_0}} H_\phi = -i \frac{\omega^2 \mu_0}{4\pi} p \frac{e^{-ikr}}{r} \sin \theta \quad (2.8)$$

In this case, the power radiation pattern becomes

$$G(\theta) = \frac{3}{2} \sin^2 \theta \quad (2.9)$$

Obviously, the radiated power is zero along the dipole moment and maximized in the azimuth plane.

The region where the simplifications apply is called the far-field or Fraunhofer region. The region in which the far field equations do not describe the field with sufficient accuracy is called the near-field or Fresnel region. The latter, which is also called the radiating near-field region, can additionally be distinguished from the reactive near field, where the stored energy in the magnetic and the electric field differ significantly.

It is not possible to define a precise cut between the near and the far field, but for practical reasons it can be assumed at a distance

$$r_{trans} = \frac{2l_{eff}^2}{\lambda} \quad (2.10)$$

where l_{eff} is the effective length of an antenna and λ the free space wave length of the emitted radiation.

As antennas are usually designed for a given frequency to be in the size of approximately one wavelength or even smaller, the Fresnel region hardly extends over more than $1 \cdot \lambda$.

2.1.7. Antenna Arrays

The combination of several identical antennas in an array allows to increase their directivity. While some parts of the radiation pattern are amplified due to constructive interference, others are canceled out.

At sufficient distance from the array, the radiation pattern is given by an element factor multiplied with an array factor. The element factor is simply the radiation pattern of one individual element of the array. The array factor contains the geometrical arrangement, adaption through phase shifting and other factors which determine the final radiation pattern [Christodoulou and Wahid, 2001, p.38f].

For very simple arrays, such as multiple dipoles in parallel or multiple patch antennas in a regular grid, it is possible to solve the array factor analytically.

2.2. Theory of Dipole Antennas

Although it is possible to derive an exact equation for the current distribution on a dipole antenna, it is usually more practical to use an approximation for the current distribution, depending on the size of the dipole compared to the examined wavelength.

For simplicity, the infinite and the small dipole are assumed to be infinitely thin, so it is sufficient to consider a one-dimensional current instead of surface and volume.

2. Theory

2.2.1. Infinite / Small Dipole

A dipole that is by far smaller than the wavelength of interest (length $< \lambda/50$) can be seen as an infinitely small dipole [Christodoulou and Wahid, 2001, p. 21f]. In this case, the current on the antenna is constant:

$$I(r, \theta = 0) = I(r, \theta = \pi) = I_0 \quad (2.11)$$

where I_0 is the feed current of the antenna.

This leads to the results already presented in section 2.1.6, modified with $\omega \cdot p = 2I_0d$ to contain the actual length d of one dipole arm:

$$\begin{aligned} E_r &= -\frac{I_0d}{2\pi} \sqrt{\frac{\mu_0}{\epsilon_0}} k^2 \left(\frac{2}{(ikr)^2} + \frac{2}{(ikr)^3} \right) e^{-ikr} \cos \theta \\ E_\theta &= -\frac{I_0d}{2\pi} \sqrt{\frac{\mu_0}{\epsilon_0}} k^2 \left(\frac{1}{ikr} + \frac{1}{(ikr)^2} + \frac{1}{(ikr)^3} \right) e^{-ikr} \sin \theta \\ H_\phi &= -\frac{I_0d}{2\pi} k^2 \left(\frac{1}{ikr} + \frac{1}{(ikr)^2} \right) e^{-ikr} \sin \theta \end{aligned} \quad (2.12)$$

In the far field case, these relations are simplified:

$$\begin{aligned} E_\theta &= i \sqrt{\frac{\mu_0}{\epsilon_0}} \frac{kI_0d}{2\pi} \frac{e^{-ikr}}{r} \sin \theta \\ H_\phi &= i \frac{kI_0d}{2\pi} \frac{e^{-ikr}}{r} \sin \theta \end{aligned} \quad (2.13)$$

For bigger dipoles, which are still much smaller than λ , the current distribution is in good approximation triangular [Christodoulou and Wahid, 2001, p. 24f]:

$$I(r, \theta = 0) = I(r, \theta = \pi) = I_0 \left(1 - \frac{r}{d} \right) \quad (2.14)$$

where d is the length of one dipole arm.

In this case, the far field has only half the strength of the infinite small dipole.

The model of the Hertzian dipole further gives the radiation resistance R_r as:

$$\begin{aligned} R_r &= \frac{2\pi}{3} \cdot Z_0 \cdot \frac{d}{\lambda^2} \\ &= \frac{2\pi}{3} \cdot Z_0 \cdot \frac{d}{c^2} \nu^2 \end{aligned} \quad (2.15)$$

with the free space impedance Z_0 .

In eq. 2.7 this gives the dependence of the electrical field on the frequency at constant voltage (since the Hertz dipole is ideal, no ohmic losses occur):

$$E \propto \sqrt{\frac{\pi^2 \nu^6}{9r^2 c^6} + \frac{\nu^4}{12c^4 r^4} + \frac{\nu^2}{144c^2 \pi^2 r^6}} \quad (2.16)$$

2.2.2. Finite Dipole

For a dipole of finite size, the current density can be approximated with a sinusoidal distribution:

$$I(r, \theta = 0, \phi) = I(r, \theta = \pi) = I_0 \sin k(d - r) \quad (2.17)$$

In that case, using the induced EMF method (see for example [Fusco, 2004, p. 79ff]), an analytical expression for the input impedance of an antenna can be given:

$$Z_A = \frac{Z_0}{i2\pi} \frac{1}{\sin^2(kd)} [4F(kd) \cos(kd) - F(2kd)] \quad (2.18)$$

with

$$F(\alpha) = e^{i\alpha} \int_{u=0}^{2\alpha} \frac{1 - e^{-iu}}{u} du - 2i \left[ka \cos \alpha + \ln \left(\frac{2\alpha}{ka} \right) \sin \alpha \right]$$

where the finite radius a of the dipole is considered [Chang, 2003, p. 647].

In this case, the field strength radiation pattern can be described as:

$$\Psi(\theta) = -2 \frac{\cos(kd \cos \theta) - \cos(kd)}{\sin \theta} \quad (2.19)$$

Following Chang [2003] these approximations are true in the region $0 \leq kd \leq 2$, while Christodoulou and Wahid [2001, p. 24] would use it for dipole antennas with arms $d > \lambda/20$.

2.3. Theory of Patch Antennas

Patch antennas are widely used in microelectronics, especially for mobile phones and wireless local area network (wlan) applications. Basically, a patch antenna consists of a patch of conducting material on one side of a dielectric substrate and metallization on the other side (which acts as ground plane). The thickness of the dielectric as well as the form of the patch determine the antenna characteristics.

Although the patch can have any form, square or rectangular shapes are preferred. The length of the patch is usually between one third and one half wavelength, the thickness of the substrate is between 0.003λ and 0.05λ . Ideally, the ground plane is infinitely large, practically it is often only little bigger than the patch. [Nakar, 2004]

Generally, patch antennas are known as narrow bandwidth, low gain antennas, which have the advantage of a small form factor, easy configurability and low production costs.

Various concepts for the theoretical prediction of patch antenna properties exist, one of the easiest will be introduced in the following subsection.

2. Theory

2.3.1. Transmission Line Model

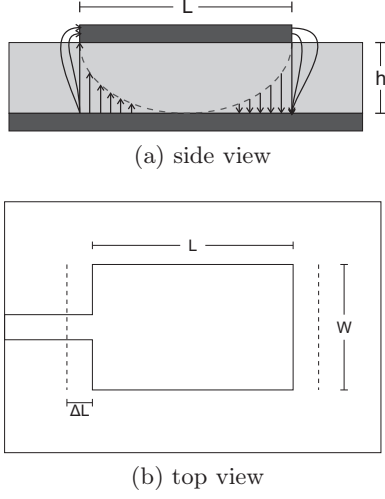


Figure 2.2.
schematic of the patch antenna

In the transmission line model, a rectangular patch antenna is represented by two slots of width W and height h , separated by a transmission line of length L . Figure 2.2a shows that not all of the electric field lines reside inside the dielectric substrate, but some make a short way through air. This leads to a quasi-TEM-mode of transmission¹. That is why an effective relative permittivity ϵ_{eff} is introduced, which is smaller than the relative permittivity ϵ_r of the dielectric, as some of the field is “lost” in the air Nakar [2004, p. 39]:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{W} \right)^{-1/2} \quad (2.20)$$

Additionally, the the extensions of the electric field besides the patch make it necessary to extend the distance between the radiating slots by a distance ΔL , seen in figure 2.2b, which can be calculated with the following empirical formula [Nakar, 2004, p. 41].

$$\Delta L = 0.412h \frac{(\epsilon_{eff} + 0.3) \left(\frac{W}{h} + 0.264 \right)}{(\epsilon_{eff} - 0.258) \left(\frac{W}{h} + 0.8 \right)} \quad (2.21)$$

The effective length L_{eff} of the patch, which is the length L extended by two ΔL , is connected with its first resonance frequency [Kumar and Ray, 2003]:

$$L_{eff} = L + 2 \cdot \Delta L \quad (2.22)$$

$$L_{eff} \cdot \nu_{res} = \frac{c}{2\sqrt{\epsilon_{eff}}} \quad (2.23)$$

Of course any harmonic of this frequency is resonant, as well as harmonics on the width of the patch. This lead to

$$\nu_{res}^{nm} = \frac{c}{2\sqrt{\epsilon_{eff}}} \sqrt{\left(\frac{m}{L_{eff}} \right)^2 + \left(\frac{n}{W} \right)^2} \quad (2.24)$$

¹A pure TEM-transmission would mean that the ratio of voltage to current is constant at any point of the line.

for modes along the length of the patch ($m = 1, 2, 3, \dots$) and along its width ($n = 1, 2, 3, \dots$).

Finally, the radiated far fields of a rectangular patch in the x-y-plane can be described with [Chang, 2003, p. 783]:

$$\begin{aligned} E_\theta &\approx -ik \frac{W}{\pi} \frac{e^{-ikr}}{r} \frac{\sin\left(\frac{kW}{2} \sin\theta \cos\phi\right)}{\frac{kW}{2} \sin\theta \cos\phi} \cos\left(\frac{kL_{eff}}{2} \sin\theta \sin\phi\right) \sin\phi \\ E_\phi &\approx -ik \frac{W}{\pi} \frac{e^{-ikr}}{r} \frac{\sin\left(\frac{kW}{2} \sin\theta \cos\phi\right)}{\frac{kW}{2} \sin\theta \cos\phi} \cos\left(\frac{kL_{eff}}{2} \sin\theta \sin\phi\right) \cos\theta \cos\phi \end{aligned} \quad (2.25)$$

A patch antenna's gain is increased if not only the length of the patch matches the frequency of the applied signal, but also the width.

To determine the optimal width the effective wavelength λ' has to be calculated depending on the resonant wavelength λ_0 and the effective relative permittivity of the substrate and the surrounding media (usually air).

$$\lambda' = \sqrt{\frac{2\lambda_0^2}{\epsilon_{air} + \epsilon_{eff}}} \quad (2.26)$$

Optimal gain is achieved if the width is half the effective wavelength, thus a standing wave is formed.

The resonant wavelength of the first resonance is known from equation 2.23:

$$\begin{aligned} \lambda_0 &= \frac{c}{2L_{eff}\sqrt{\epsilon_{eff}}} \\ W &= \frac{\lambda'}{2} \\ &= \frac{2L_{eff}\sqrt{\epsilon_{eff}}}{\sqrt{2}(\epsilon_{air} + \epsilon_{eff})} \end{aligned} \quad (2.27)$$

Choosing $\epsilon_{air} = 1$, equation 2.27 can be rewritten to give the optimal L/W relation:

$$\frac{W}{L} = \sqrt{\frac{2\epsilon_{eff}}{\epsilon_{eff} + 1}} \quad (2.28)$$

2.3.2. Cavity Model

An extended way of describing a patch antenna is to model the region between the patch and the ground plane as a cavity. This is based on the idea that due to the small thickness of the dielectric, the field between patch and ground plane only has a z -component and does not vary significantly in that region.

2. Theory

Due to these conditions, the electric field only has a z -component E_z which must meet the wave equation:

$$\frac{\partial^2 E_z}{\partial x^2} + \frac{\partial^2 E_z}{\partial y^2} + k^2 E_z = i\omega\mu_0 J \quad (2.29)$$

where J is the electric current density. [Garg and Bahl, 2000, p. 258]

Applying the boundary conditions given by the electric (front side and ground plane) and the magnetic walls (sides of the cavity), the solution to this problem can be expressed in form of modes [Chang, 2003, p. 785f]:

$$E_z = \sum_{m,n} \frac{i\omega\mu_0}{k_e^2 - k_{mn}^2} \frac{\langle J\psi_{mn} \rangle}{\langle \psi_{mn}\psi_{mn} \rangle} \psi_{mn} \quad (2.30)$$

with

$$\langle J\psi_{mn} \rangle = \iiint_{feed} J\psi_{mn}^* \langle \psi_{mn}\psi_{mn} \rangle dV$$

and introducing the complex dielectric constant ϵ_d in k_e

$$\begin{aligned} k_e &= \omega\sqrt{\mu_0\epsilon_d} \\ \epsilon_d &= \epsilon_0\epsilon_r (1 - i\delta) \end{aligned} \quad (2.31)$$

Using ϵ_d , various loss effects can be included in the calculation. For the comparison of photovoltaic power cells with patch antennas, especially the possibility of including ohmic losses in δ is of interest.

Since the impedance can be found dividing the feed-voltage through the current and the feed voltage is proportional the the electric field, the impedance is inversely proportional to $(k_e^2 - k_{mn}^2)$. A lossy dielectric means an increase in δ and consequently in k_e^2 , thus reducing the impedance, respectively the field strength. Further, the bandwidth of an antenna is increased in this case.

2.4. Photovoltaic Power Generators

Photovoltaic power generators transform the energy of incident radiation via quantum energy conversion into electrical power. Although many different types of photovoltaic power converters exists, all share the same basic working principle and have many design aspects in common. The following section focuses on silicon based cells, which are characterized by thick crystalline silicon substrates and metallic grids as front contacts. Thin film technologies will be explained in principle, but no detailed discussion will be carried out.

2.4.1. Working Principle

The technology of photovoltaic devices is based on the inner photoelectric or photovoltaic effect, which causes the excitation of electrons by photons and their movement through an inner electric field.

A photon of sufficient energy, which is absorbed in the semiconducting material, can excite an electron from the valence band to the conduction band. This generates an electron-hole pair, which exists for a certain time before they recombine. A statistical measure for this time period is the so called lifetime. In a solar cell, this pair can be separated by an electric field which is usually realized by a pn-junction². The electron-hole pair performs a statistical movement in the crystal, so there is a reasonably high probability for the pair to enter the region where the inner field separates the carriers, if its lifetime is long enough. The separated charges create a voltage difference between both sides of the pn-junction, which can be used to drive an external load.

Since the current generated by a solar cell depends on the spectral distribution and intensity of the incident light but hardly on the connected load (as long as the load remains small enough), it is sensible to describe the solar cell as a current generator with an internal loss mechanism. Most of the cell characteristics can be described by the determination between the voltage and current, the I-V-curve. Some parameters of special importance can be derived from this curve, such as the open-circuit-voltage, the short-circuit-current, the shunt resistance, the series resistance, the fill factor and others.

For details see for example [Wagemann and Eschrich, 1994], [Nelson, 2003] or [Goetzberger and Hoffmann, 2005].

2.4.2. Parts of a Solar Cell

For the analysis of the reaction of a solar cell to external electromagnetic fields it is important to analyze the individual parts a cell usually consists of. The following sections describe the relevant parts of a cell, starting from the substrate and going from the forming of a pn-junction to the application of front grid and back metallization.

2.4.2.1. Substrate

Solar cell technologies are distinguished by the substrate that is used. The most advanced technology is that of mono- or polycrystalline silicon material. Since these cells were developed starting from computer chip electronics, cells are made

²Alternatively metal-oxide-semiconductor structures, Schottky barriers or charge carrier density gradients are in use, but less common.

2. Theory

out of doped silicon wafers. The wafers are either cut out of bulk silicon (polycrystalline) or out of ingots created by the Czochralski process (mono crystalline). During crystallization additional electrical active dopants are added - usually boron, which creates p-doping. This means, that the addition of a group three element to the group four element silicon reduces the number of electrons compared to the number of single atoms in the crystal, which means the creation of additional holes or positive charge carriers above the intrinsic level. In further description, it will be assumed that the wafer is p-doped, although it is possible to carry out all steps with n-doped wafers. [Goetzberger and Hoffmann, 2005, p. 23-27]

Wafers are preferentially quadratically shaped with a side length ranging from 100 mm to 300 mm, where 150 mm are currently most common. Newly built production lines are optimized for 200 mm and 300 mm.

Wafer thickness usually lies between 200 μm and 300 μm , with advanced sawing techniques even less.

The silicon substrate has a dielectric constant $\epsilon = \epsilon_r \epsilon_0 = 10 \dots 12 \cdot \epsilon_0$ and typically a resistivity of 1 Ωcm , which corresponds to approximately $1 \cdot 10^{16} \text{ cm}^{-3}$ ionized acceptors at room temperature.

2.4.2.2. pn-Junction

Starting with a p-doped wafer, the pn-junction is created by diffusion of a n-type dopant, mostly phosphorous, on one surface, thus compensating the present acceptors and additionally introducing a concentration of $> 10^{20} \text{ cm}^{-3}$ donors in a layer of less than 1 μm . The fixed ions in the silicon matrix on either side of the junction create the electric field which separates the generated electron hole pairs. The region inside the junction is depleted of mobile charge carriers, so the junction basically can be considered as a voltage dependent capacitor. [Goetzberger and Hoffmann, 2005, p. 30f], [Nelson, 2003, p. 145f]

The pn-junction introduces an inhomogeneity in the dielectric constant of the cell substrate, which may have influence on the interaction with electromagnetic fields. The same is true for grain boundaries in multi-crystalline cells, as they are discontinuities in the dielectric function.

2.4.2.3. Front Grid

To collect the generated carriers from the light exposed front side of a cell, it is necessary to apply a metal grid to the cell.

For silicon solar cells, numerous approaches to front grid design exist, but the most widely spread design nowadays with respect to physical necessities and technological limitations is the H-pattern (fig. 2.3). This pattern consists of a series of

parallel thin fingers and two broad bus bars perpendicular to the fingers. The exact proportion depend on the conductivity of the grid parts, but usually the bus bars can be found at $1/4$ and $3/4$ of the cell width to minimize the resistance of the grid.

For economic reasons the front grid is most frequently screen or jet printed. The main metallic component of the used paste is silver for its high conductivity, although there exist several approaches to replace Ag with Al as much as possible, for reasons of lower price and higher material availability. For the interconnection of the cells to an array, metal bands are soldered on the bus bars. [Nelson, 2003, p. 188]

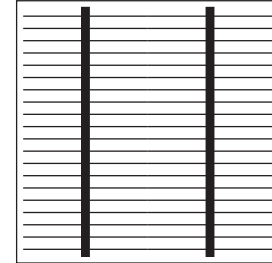


Figure 2.3.
H pattern front grid

The resistivity of the used paste is around $10^{-6} \Omega\text{m}$, while that of the doped silicon is of the magnitude $10^{-2} \Omega\text{m}$, so the conductivity of the grid is obviously much higher than that of the silicon surface.

2.4.2.4. Back Metallization

Usually the back side of solar cells is fully covered with a metallic layer with good conductivity like aluminum. This serves primarily to collect charge carriers, but secondarily the diffusion of the used metal not only removes a potential n-doped layer due to the diffusion technology on the backside but can even create an additional p^+ layer which repels charge carriers that move in the “wrong” direction. The back-metallization is usually also printed on the cell excluding its edges.

As the back metallization forms a continuous, highly conductive plane on the backside of the cell, it may act as a reflector not only to transmitted light but to electromagnetic radiation as well, which is important for the patch model given in section 2.5.2.

2.4.3. Thin Film Cells

New approaches focus on thin-film-cells, because less material is required. Various techniques exist to generate films of few micrometers thickness on a substrate (usually glass). Current commercial products are based on amorphous silicon

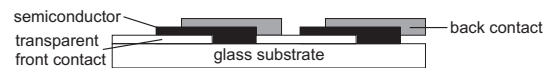


Figure 2.4.
structure of a thin film cell (illumination from the lower side of the figure)

2. Theory

(aSi), Cadmium-Telluride (CdTe), Copper-Indium-Selenide (CIS) and Copper-Indium-Gallium-Selenide (CIGS). The pn-junction is created by successive deposition of different materials on the substrate, with a step of deposition of a transparent conductor which is used as front grid before and deposition of a second conductor as back metallization afterward. After each deposition step a laser scribing step may be made, which is used to cut the film and form the desired connections as can be seen in figure 2.4.

Currently produced solar modules based on thin film cells often exceed the size of modules made of crystalline silicon cells, but their electrically active area is significantly thinner.

For more information on thin film solar cells see for example [Wagemann and Eschrich, 1994, p. 102-126] or [Goetzberger and Hoffmann, 2005, p. 59-70].

2.5. Comparison Solar Cell - Antenna

When comparing a solar cell to an antenna, two approaches can be followed.

The first is the dipole antenna model, which focuses on the front grid. As the resistance of the p-doped silicon on the front side is higher than that of the front grid, the silicon is seen as a dielectric layer which does not interact with incoming radiation.

The second approach is the patch antenna model, which focuses on the cell volume considering the front side as a real conductor. The front grid is ignored and it is assumed that the whole solar cell acts as a rectangular patch antenna.

2.5.1. Comparison with Dipole Antenna

The comparison of a solar cell with a dipole antenna is more precisely the comparison of the front grid of the cell with an dipole antenna array.

2.5.1.1. single dipole array

Although the H grid is the most widespread design, for simplicity only one bus bar will be discussed first. In this case, the cell will be assumed to be rectangular with one bus bar in the middle of the longer side and several fingers parallel to the short side. As mentioned in section 2.1.7, it is possible to obtain the far field of the array by multiplication of the field of a single dipole (EF) with an array factor (AF).

The array factor can be found by geometrical considerations following figure 2.5 (the derivation can be found in [Christodoulou and Wahid, 2001]), while the

2.5. Comparison Solar Cell - Antenna

element factor is the radiation pattern of a single dipole (here again shown in z-direction). As a dipole in z-direction has non-zero components only in θ -direction, unit vectors are omitted. This gives for an N -element array of dipoles with the length $2d$ at a distance D and with the wavenumber k in spherical coordinates:

$$EF = \Psi_e(\theta) = -2 \frac{\cos(kd \cos \theta) - \cos(kd)}{\sin \theta} \quad (2.32)$$

$$AF = \frac{\sin\left(\frac{N\psi}{2}\right)}{N \sin\left(\frac{\psi}{2}\right)} \quad (2.33)$$

with

$$\psi = kD \sin \theta \cos \phi + \varphi$$

The phase shift φ between adjacent elements can be assumed to be identical to their distance D , as they are directly connected, which gives

$$\varphi = kD$$

Multiplication gives

$$\Psi_{tot} = 2 \frac{\cos(kd) - \cos(kd \cos \theta)}{\sin \theta} \cdot \frac{\sin\left(\frac{N}{2}kD(\sin \theta \cos \phi + 1)\right)}{N \sin\left(\frac{1}{2}kD(\sin \theta \cos \phi + 1)\right)} \quad (2.34)$$

which can be transformed to the power radiation pattern by equation 2.4.

At sufficiently low frequencies, the pattern is toroidal like that of a single dipole as shown in fig. 2.6a. In this case the pattern is independent of ϕ , no directivity in the x-y-plane exists.

At higher frequencies, the pattern changes as illustrated by fig. 2.6b. There is practically no radiation in positive x-direction and increased radiation in negative x-direction. Inversion of the phase shift would turn the pattern in positive direction.

For an actual solar cell it has to be considered, that the back-metallization would act as a reflector and would thus additionally modify the radiation pattern.

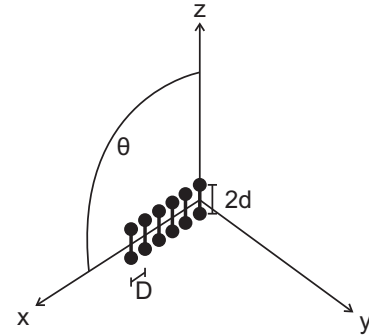


Figure 2.5.
schematic of a single row
dipole array

2. Theory

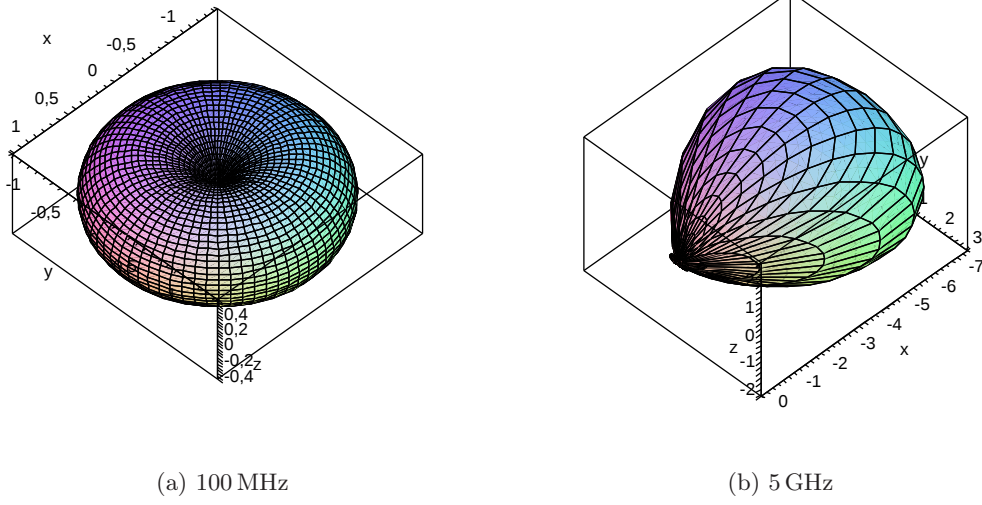


Figure 2.6.
power radiation pattern of a single row dipole array at 100 MHz and 5 GHz,
with $d = 2.5$ cm, $N = 19$ and $D = 5$ mm

2.5.1.2. double dipole array

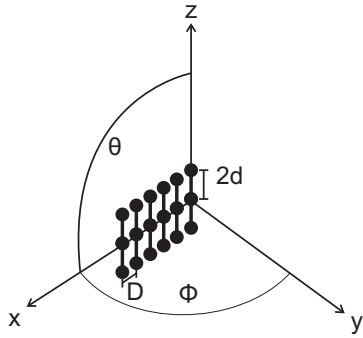


Figure 2.7.
schematic of a double row dipole
array

In the H design two bus bars are printed in parallel over the length of a cell at $1/4$ and $3/4$ of the cell width. Multiple fingers are perpendicular to the bus bars. Assuming a symmetric current distribution, a single element of an according antenna array is a small part of one bus bar with one finger at each side. An array of two by n elements (depending on the number of fingers) would cover the whole solar cell.

The array factor for this case can be obtained by multiplication of the array factor of the single row dipole array in x direction with the array factor of an array consisting of only two dipoles in

z-direction:

$$AF_z = \frac{\sin(\psi_z)}{2 \sin\left(\frac{\psi_z}{2}\right)} \quad (2.35)$$

$$AF_x = \frac{\sin\left(\frac{N\psi_x}{2}\right)}{N \sin\left(\frac{\psi_x}{2}\right)} \quad (2.36)$$

with

$$\begin{aligned} \psi_z &= 2kd \cos \theta \\ \psi_x &= kD \sin \theta \cos \phi + kD \end{aligned}$$

Since both bus bars are contacted and cable length usually does not differ too much, it can be assumed that there is no phase difference between both dipoles, so there is no phase difference in z direction.

Multiplication gives:

$$\begin{aligned} AF_{total} &= AF_z \cdot AF_x \\ &= \frac{\sin(2kd \cos \theta)}{2 \sin(kd \cos \theta)} \frac{\sin\left(\frac{N}{2}kD (\sin \theta \cos \phi + 1)\right)}{N \sin\left(\frac{1}{2}kD (\sin \theta \cos \phi + 1)\right)} \end{aligned} \quad (2.37)$$

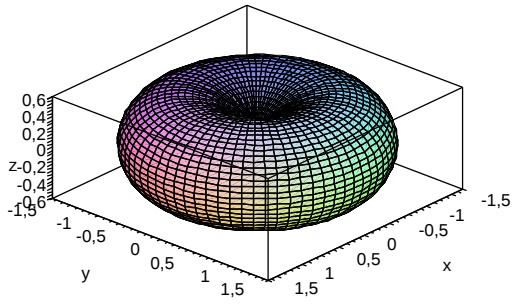
The element factor remains the same.

$$EF = -2 \frac{\cos(kd \cos \theta) - \cos(kd)}{\sin \theta} \quad (2.38)$$

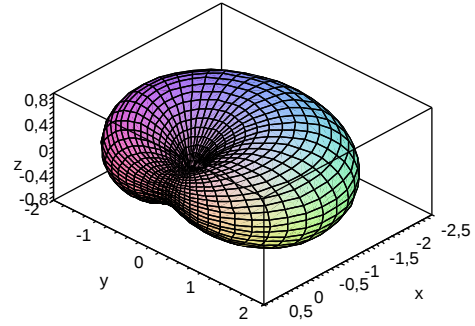
Graphical assessment of the double row dipole model shows that the second row of dipoles increased the effect which could already be seen at the single row dipole. Additionally, pattern changes occur at lower frequencies. While the power radiation pattern is toroidal at low frequencies, it shows increased directivity when approaching the resonant frequency of a single element (6 GHz in the visualized case). The series of pictures in figure 2.8 shows the development.

It is of interest to investigate the behavior in dependence of the frequency in forward ($\phi = 0$), backward ($\phi = \pi$) and side ($\phi = \pi/2$) direction. In forward direction, the power of the radiated field increases exponentially while it decreases exponentially in backwards direction. The latter varies sinusoidally, which results in the frequency dependent occurrence of back lobes. The same is true for side lobes, which vary much slower than the back lobes. These three cases are shown in figure 2.9.

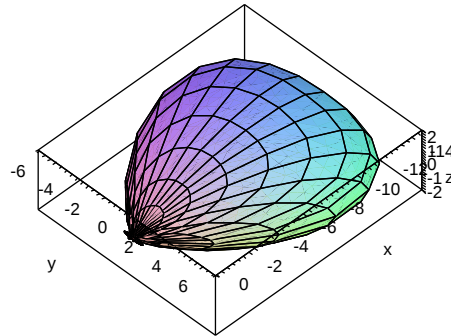
2. Theory



(a) 100 MHz



(b) 1 GHz



(c) 5 GHz

Figure 2.8.
power radiation pattern of a double row dipole array at various frequencies,
with $d = 2.5$ cm and $D = 5$ mm

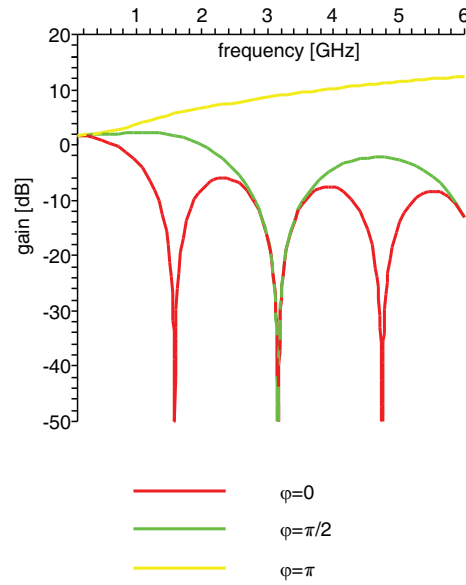


Figure 2.9.
gain [dB] versus frequency [Hz] of a double row dipole array, with $d = 2.5$ cm
and $D = 5$ mm at different angles

The impedance decreases with the number of single antenna elements, while the resonant frequency remains that of a single element. A comparison of the real part of the impedance of a single dipole element with a length of 5 cm and a 10×10 cm patch antenna can be found in figure 2.10. It can be seen that the first resonance of the dipole occurs at a much higher frequency than that of the patch.

2. Theory

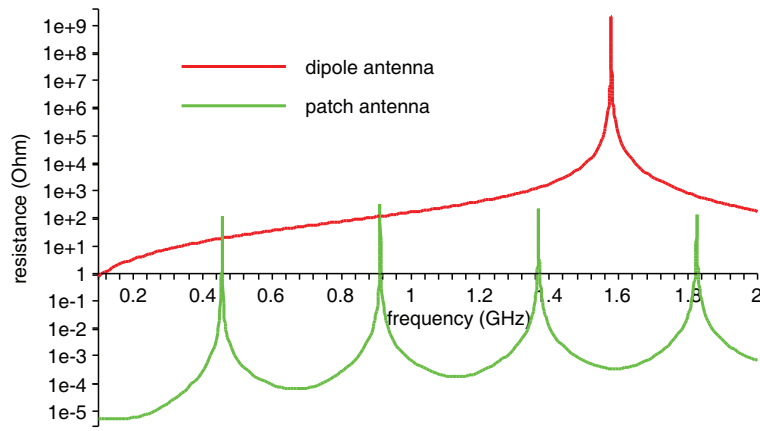


Figure 2.10.
real part of the impedance of a dipole antenna with $d = 2.5$ cm and a
 10×10 cm patch antenna

2.5.2. Comparison with Patch Antenna

When a patch antenna is compared to a crystalline solar cell, the similarities become obvious. The silicon substrate has a relative permittivity of approximately 10 – 12, which is in the typical range for patch antennas (silicon itself is an occasionally used substrate). However, due to the high doping, it has a high loss current. The back metallization has similarities to a ground plane, while the front grid may well act as the patch. Depending on the front grid design and the surface resistance of the front layer, either the whole front of the cell may act as one patch, or the bus bars may act as two parallel patches, neglecting the collecting fingers.

Thin film solar cells may be even more similar to patch antennas, since their front contact actually is a continuous layer, while the dielectric layer is extremely thin.

2.5.2.1. Single Patch

Assuming a thin highly conductive front surface layer on a quadratically shaped cell, the grid will be ignored and only its boundaries will be taken as the boundaries of a single patch. On a 100×100 mm wafer this would result in a approximately 95×95 mm patch. Since the simple transmission line model will be used, the size of the back metallization will be ignored. The feed in point will also be ignored, as most models do not allow to use two feed in points in parallel and the position of the feed point is only important for adjusting the impedance.

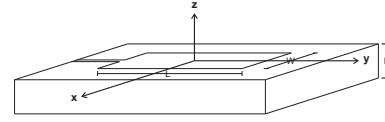


Figure 2.11.
schematic of a patch antenna

Comparing the side length to the wafer thickness of approximately $300 \mu\text{m}$

$$\frac{300 \cdot 10^{-6}}{95 \cdot 10^{-3}} \approx 0.3\%$$

it can be seen that the effective relative permittivity described in eq. 2.20 does not change for more than 1%, even less for a 300×300 mm cell with $150 \mu\text{m}$ thickness. For thin-film cells the correction can be entirely ignored, as the effect decreases with thickness.

The patch length correction for the fringing fields is given in equation 2.21. Again for the 100×100 mm wafer and an effective dielectric constant of 12, the length extension is about 1%, much less for thinner wafers.

Using equation 2.24 a resonance frequency of approximately 456 MHz for the 100×100 mm wafer is found; for the 300×300 mm wafer 148 MHz.

2. Theory

Comparison with the dipole model shows that resonance occurs at significantly lower frequencies (see figure 2.10).

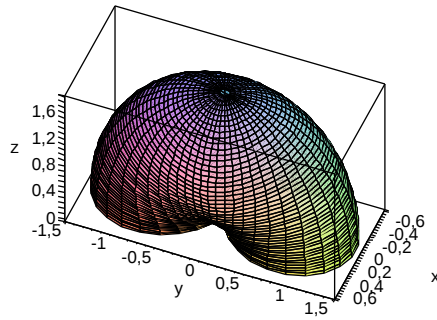
At the first resonance frequency, the radiation pattern is toroidal like that of a dipole. It exists only in positive z-direction, since the ground plane is assumed to be infinite (compare 2.8a and 2.12a). At the second mode (as the patch is quadratic, all modes are TEM) the radiation pattern is directed in z-direction, which increases with increasing frequency. At the sixth harmonic, the pattern becomes dominated by side lobes, which can be seen in figure 2.12.

2.5.2.2. Two Patches

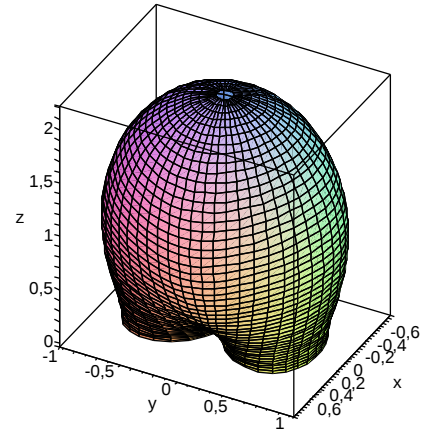
In this case, only the metal bus bars are taken in consideration. A single bus bar of 95 mm length and 3 mm width would result in a reduction of the relative permittivity from 12 to 10.7. In this case, the effective length of the patch is practically unaffected. The first resonance occurs at a similar frequency as for the single patch at approximately 480 MHz. The radiation pattern of the two parallel long patches however, is practically identical with that of one single patch.

As all resonant frequencies lie well above 20 MHz, no resonances are expected to be found in the experimentally examined range. The low frequency range for investigation was chosen since higher frequencies have already been covered for example by the work of Wada et al. [2005] and Bendel et al. [2002].

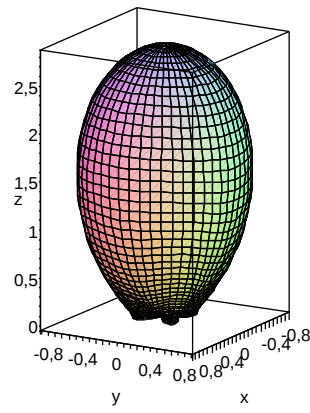
2.5. Comparison Solar Cell - Antenna



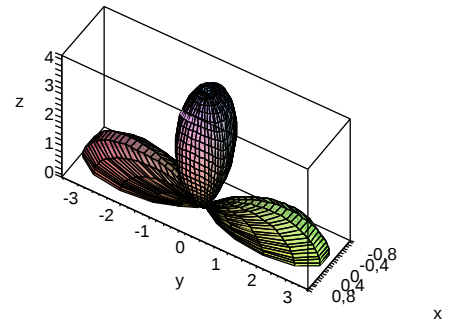
(a) first harmonic



(b) second harmonic



(c) third harmonic



(d) sixth harmonic

Figure 2.12.
power radiation pattern of a quadratic 95 mm side length patch antenna at
several harmonics

2. *Theory*

3. Setup

A well defined signal (by means of amplitude, frequency and phase) was emitted by a dipole antenna and the received signal at the samples was analyzed. The setup for the conducted experiments consisted of a lock-in amplifier with built-in sine wave generator, a signal generator, a dipole antenna and the devices under test (DUT). A plotter was used to examine position dependent effects.

In order to take advantage of the high sensitivity of the lock-in amplifier detection, two operation modes were used:

1. Below 100 kHz, the emitted signal is directly generated by the the signal generator with which the lock-in amplifier synchronizes.
2. For higher frequencies the external function generator produces a carrier signal. The internal generator of the lock in amplifier is used to produce a modulation signal which is amplitude modulated to the carrier signal by the function generator. This mode is used from 100 kHz up to 20 MHz.

A diagram of the setup can be found in fig. 3.1.

In the first case, the sync output of the function generator is connected to the reference input of the lock-in amplifier (indicated by the dotted line in the figure). The output of the function generator is directed to the sending antenna by a 50 Ω coaxial cable, and the DUT is connected with the input of the lock-in amplifier via a 50 Ω feed-through resistor.

In the second case, instead of connecting the sync output of the function generator with the reference input, the sine output of the internal wave generator of the lock-in amplifier is connected to the modulation input of the function generator (dashed line in the figure). The signal paths to the antenna and from the DUT remain unchanged.

All parts are described in more detail in the following sections.

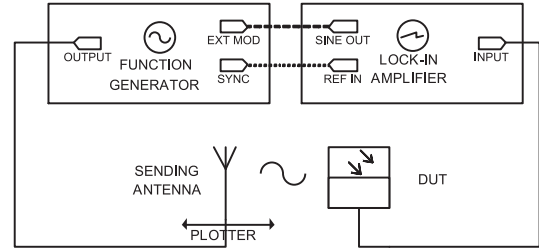


Figure 3.1.
schematic of the experimental setup
Refer to the text for details
concerning the interconnection
between lock-in amplifier and
function generator.

3. Setup

The function generator and the lock-in-amplifier are connected to a PC via GPIB-interface. A program was designed to automate the recording of data in the full frequency range including harmonics and the movement of the sending antenna.

Antenna and DUT are placed in an electromagnetically shielded compartment, which has the size of $60 \times 51 \times 45 \text{ cm}^3$ (length $\times$ depth $\times$ height). The shielding is achieved by the use of grounded 0.5 mm galvanized steel sheets.

3.1. Function Generator

The function generator was used to produce an emitted signal. The device is an Agilent 33220A Function / Arbitrary Waveform Generator with a frequency range for sinusoidal waves from 1 μHz to 20 MHz. Its maximum harmonic distortion is -35 dBc .

The function generator is able to produce an peak-to-peak output voltage up to $20 V_{\text{pp}}$ when operated in open-circuit mode, and $10 V_{\text{pp}}$ into a 50Ω resistor. If not otherwise stated, it is run in open-circuit mode due to the high impedance of the sending antenna, and the maximum possible voltage is used.

Although the range for amplitude modulation was selectable between $0 - 120\%$, it was kept at constant 100% . The available frequency for modulation ranges from 2 mHz to 20 kHz. We used modulation frequencies between $1 - 5 \text{ kHz}$, usually $\sqrt{2} \text{ kHz}$ to avoid unwanted resonance effects between modulation and carrier frequency. Unmodulated signals were in the range from 10 Hz to 100 kHz.

3.2. Lock-In-Amplifier

range	time constant
10 – 200 Hz	3 s
250 – 1000 Hz	1 s
2 – 100 kHz	300 ms
0.1 – 20 MHz	100 ms

Table 3.1.
used time constants

The lock in amplifier, a Stanford Instruments SR830 dual phase digital lock in amplifier, serves as frequency and phase sensitive amplifier for the received signal with a built in configurable sine wave generator.

Its reference channel is able to produce sine waves in a range from 0.1 mHz to 102 kHz at a distortion of -80 dBc .

The maximum amplitude is $5 V_{\text{rms}}$. It

was kept at $4.5 V_{\text{rms}}$, because of decreasing signal stability above this level.

The signal channel has a sensitivity from 2 nV to 1 V, with a maximum typical noise of $6 \text{ nV}/\sqrt{\text{Hz}}$. Line filters for 50 and 100 Hz as well as a bandpass filter with 24 dB/oct are installed.

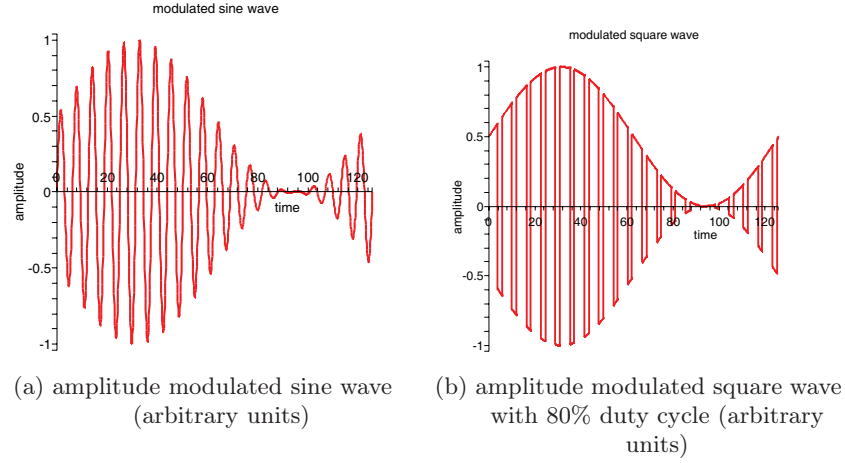


Figure 3.2.
different forms of amplitude modulated carrier waves

Available integration time constants range from $3\text{ }\mu\text{s}$ to 30 ks . In our experiment time constants were set frequency range dependent according to table 3.1. A settling time of ten times the actual time constant before making measurements was programmed. Usually 10 measurements were taken with a delay of one time constant and their mean and standard deviation calculated.

The LIA provides measurements of harmonics up to the frequency limit of the reference channel. In most cases harmonics up to the 4th were recorded. No harmonics could be taken in carrier wave operation mode.

The working principle of the lock-in-amplifier is to multiply the ingoing signal with the reference signal and integrate over the timeconstant, which effectively eliminates all signals with frequencies that are not equal to the reference frequency¹. Since amplitude modulation on a sinusoidal carrier wave generates a symmetrical output (see fig. 3.2a), integration always yields zero. No demodulator was used in order to keep a low noise level. Instead, a square with with 60% duty cycle was used as carrier wave. Figure 3.2b illustrates that in this case the positive part of the wave dominates, and thus, integration is not zero.

Due to this setup, the observation of the received signal of the LIA is frequency dependent. The function generator output was directly recorded with the lock-in amplifier to record a correction curve, which can be seen in fig. 3.3a. Additional emission of radiation at harmonics of the carrier wave frequency occurs, the amplitude of the harmonics decreases with increasing frequency. A theoretical pre-

¹The lowest frequency that is eliminated is determined by the timeconstant, since the integration is only zero if it is done over a whole cycle.

3. Setup

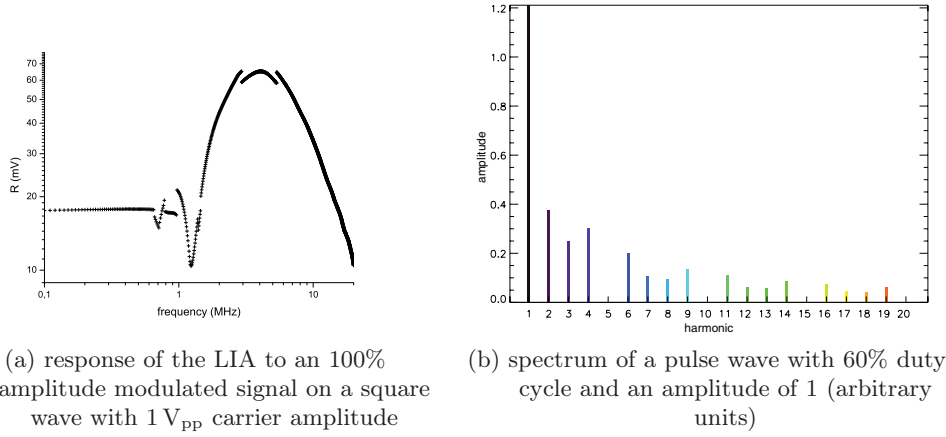


Figure 3.3.

LIA response to and spectrum of an amplitude modulated square wave

diction² for the spectrum can be seen in figure 3.3b.

Overshooting of the modulation leads to an effective amplitude of the sending signal of $12 V_{pp}$.

3.3. Sending Antenna

The sending antenna in use is made of two parts of copper wire with a diameter of $\approx 1.8 \text{ mm}$ and 0.2 mm of electrical insulation. It is connected to the signal generator with a coaxial cable of 1 m length. A photograph of the antenna can be seen in figure 3.4.

Part (a) of figure 3.5 shows the gain, as described in 3.5, of the antenna in the direct sending mode. This is the mode in which the antenna is directly fed with a sinusoidal signal. The gain increases hardly in the range from 10 to 200 Hz , and shows several spikes: at 50 Hz , 100 Hz and 150 Hz . These are probably effects of the notch filters, which have a too much dampening effect. Above that, the increase appears linear in the double logarithmic scale, with an increase of one order of magnitude per order of magnitude in frequency, which means a linear increase of the field strength with the frequency. Using equation 2.16 with values

²The pulse was defined by $f(t) = \begin{cases} A & |t| < \Delta/2 \\ 0 & \Delta/2 < |t| < \pi \end{cases}$ which gives the following Fourier series:

$$f(t) = \frac{A\Delta}{\pi} \left[\frac{1}{2} + \sum_1^{\infty} \frac{\sin(k\Delta/2)}{k\Delta/2} \cos kt \right]$$

with $\Delta = \frac{6}{5}\pi$ for the 60% duty cycle and an amplitude of $A = 1$

3.3. Sending Antenna

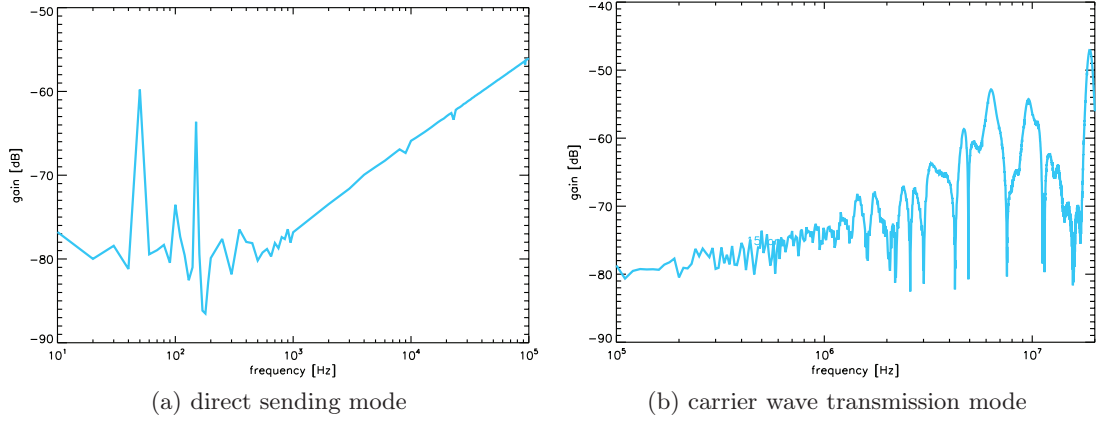


Figure 3.5.
gain of the 20 cm dipole antenna in different modes

from the setup, one gets a proportionality of

$$E \propto 10^{-6} \cdot \sqrt{10^{-33}\nu^6 + 10^{-16}\nu^4 + 10\nu^2} \quad (3.1)$$

where it is obvious that for low frequencies the increase is linear, so agreement between theory and experiment is given.

In part (b) of figure 3.5 the gain in the range from 100 kHz to 20 MHz is displayed. In this range, the reference signal is amplitude modulated on a carrier signal. The characteristics that can be seen here can not be predicted by the simple model.

The antenna is mounted on the pen carrier of an HP 7475A plotter, so the measurement at different distances between sender and receiver can be automated. The resolution of the plotter allows the distance to be controlled with a precision of 0.0248 mm/step.

Since antenna impedance extends over six orders of magnitude, impedance matching of the antenna was not made. The use of a balun was also omitted, as it would have been necessary to match it to the frequency as well.



Figure 3.4.
20 cm dipole antenna,
moveable in a horizontal
slot

3. Setup

3.4. Restrictions

The experimental setup imposes some restrictions on the possible measurements and creates several sources of errors.

One source of errors is the use of a square wave carrier signal. The produced harmonics add to the total energy transfer and thus increase the received amplitude. Although the amplitude of the harmonics decreases relatively fast, their contribution could still be high, since the impedance of the dipole antenna increases with frequency.

The frequency dependence of the antenna's impedance is another restriction on the experimental setup. In regions far below the resonant frequency of the dipole antenna, its impedance increases approximately quadratically with the frequency. Thus, matching the impedance of the antenna to the source and the transmission line impedance would require enormous effort. The impedance mismatch represents a discontinuity in the signal path and produces reflections of the signal, which reduce the transmitted power and may additionally create standing waves on the transmission line. The latter is of little importance, since the coaxial cable that acts as transmission line is placed outside the compartment. Impedance matching to the DUT is impossible per se, since the impedance of the DUT is unknown.

Another discontinuity occurs at the change from coaxial cable to the antenna or the DUT. The cable is a so-called unbalanced transmission line, while the parallel feed lines of the antenna are balanced³. This is another possibility for wave reflection.

The source of possibly largest errors are reflections of the emitted wave on the electrical shielding, which may be the explanation for the behavior in the > 100 kHz range that could already be seen at the reference antenna gain (fig. 3.5b). Figure 3.6 shows results for the reference antenna at the same distance (10 cm) and alignment but at different positions in the compartment.

Due to these restrictions, it is not possible to make power measurements and consequently no quantitative results can be retrieved from the recorded data. A qualitative comparison of the DUT and the reference antenna is possible.

3.5. Data Evaluation

Due to the wide range of the measured values, it is convenient to use a logarithmic scale for displaying them, which implies the use of dB as unit. As the Bel is defined

³A balanced line carries a symmetric wave with respect to ground potential, an unbalanced line an asymmetric wave.

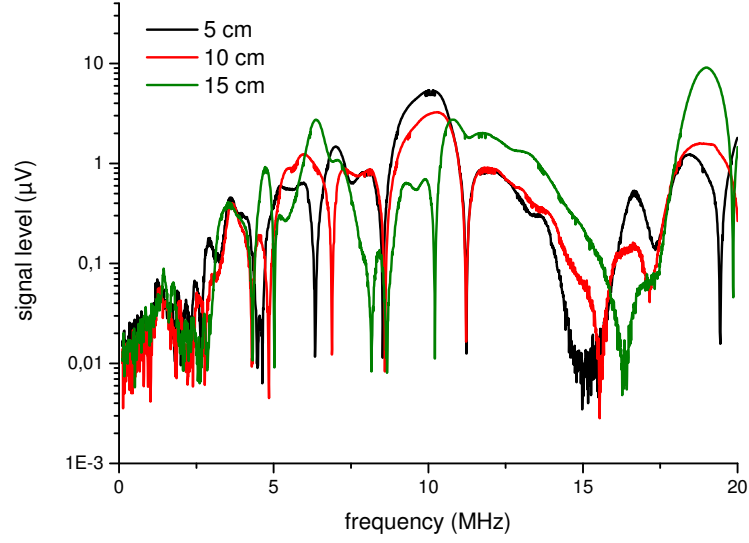


Figure 3.6.
signal level of the reference antenna at constant distance at different positions
(measured from the left compartment wall) in the compartment

as the logarithm to base 10 of a value relative to a reference

$$[\text{dB}] = 10 \cdot \log_{10} \frac{\text{value} [\text{u}]}{\text{reference} [\text{u}]} \quad (3.2)$$

it is necessary to choose a reference value.

Two approaches which we have used for data evaluation will be introduced in the following sections.

3.5.1. Comparison with Sender

An easy choice for the reference voltage is the voltage at the sending antenna, which is essentially the output voltage of the function generator. In this case, the gain refers to a voltage and can be calculated by

$$G_V [\text{dBV}] = 10 \cdot \log \frac{U_{DUT}}{U_{\text{applied}}} \quad (3.3)$$

The unit is denoted as dBV, to emphasize that voltages are compared (instead of powers).

3. Setup

It has to be taken into account, whether peak-to-peak voltage (V_{pp}) or the root-mean-square of the voltage (V_{rms}) is measured. For a sinusoidal wave transformation from V_{pp} to V_{rms} is done by dividing V_{pp} through $\sqrt{2}$:

$$[V_{rms}] = \frac{[V_{pp}]}{\sqrt{2}} \quad (3.4)$$

Additionally, if a signal is amplitude modulated on a carrier frequency the effective amplitude of the reference signal has to be taken into account.

3.5.2. Comparison with Receiver

Another possibility is to compare the received signal of a sample with the value obtained by a reference antenna.

In this case, a gain G is defined by:

$$\begin{aligned} G [\text{dB}] &= 10 \cdot \log \frac{U_{DUT}}{U_{ref}} \\ &= 10 \cdot \log U_{DUT} - G_{ref} \end{aligned} \quad (3.5)$$

For convenience, the value

$$G_{ref} = 10 \cdot \log U_{ref} \quad (3.6)$$

is introduced.

Although again voltages are compared, in the case the unit will be denoted as dB for easiness of recognition of the used reference.

This way of displaying the measured values has the advantage that no correction for background noise etc. has to be made, and that it is not necessary to show the reference antenna curve for comparison. The main disadvantage of this method is that two measurements cycles have to be made to record the signal of the solar cell and the signal of the reference antenna. Once the position of the receiver in the shielded compartment is not precisely the same for both measurements the frequency dependence of the two signals is somewhat shifted (see fig. 3.6), thus leading to two additional peaks in the gain instead of canceling out.

4. Samples

4.1. Laboratory Cells

To be able to examine the influence of different parts of solar cells on their reaction to external electromagnetic fields, several industry wafers were partly processed in the laboratory.

The wafers are poly-silicon wafers, Boron doped at a concentration of 10^{16} cm^{-3} and $10 \times 10 \text{ cm}$ in size.

Two of them were processed with phosphorous doping, application of a H front grid, an aluminum back plate and edge grinding (fig. 4.1).

On two additional wafers only a front grid was printed. One of them was back contacted using adhesive copper foil.

As no phosphorous doping was applied, no p-n-junction was present. Due to the high resistance of doped silicon compared to the used silver paste for the front grid, the silicon wafer can be considered as an insulator when the grid is contacted.

The front grid consists of 19 fingers at a distance of 5 mm and a length of 94 mm, connected by 2 bus bars which are positioned at 25% and at 75% of the width.

The wafers are electrically connected to the LIA through contact with copper foil on the carrier, which is soldered to the cable shielding. The inner conductor of the coaxial cable ends in a retractable steel tip, which is placed on one of the bus bars (see fig. 4.2).

Table 4.1 lists the four wafers with their processing state.

Figure 4.3 shows the I-V-characteristics of samples E and F in the dark, at room temperature. It can be seen that especially for sample E the series resistance is extremely high.

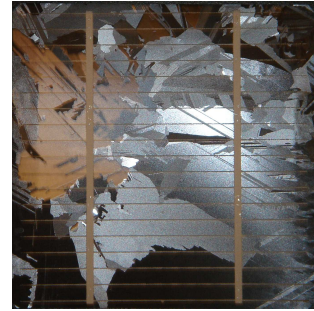


Figure 4.1.
cell with standard
H-front grid design

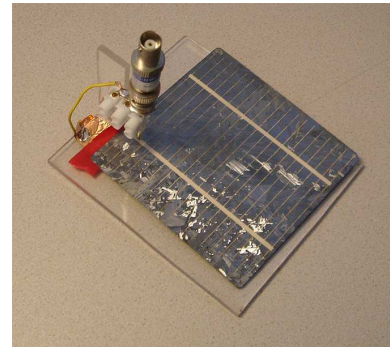


Figure 4.2.
cell contacted on carrier

4. Samples

sample	processing state
A	no pn-junction, front grid
B	no pn-junction, front grid, back metallization
E	working cell (high series resistance)
F	working cell

Table 4.1.
used wafers

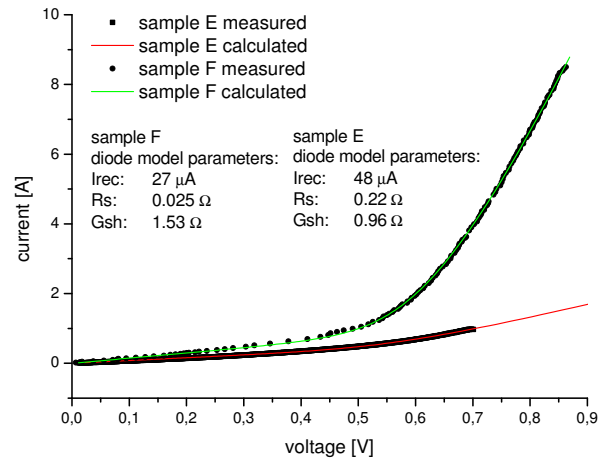


Figure 4.3.
I-V characteristics of samples E and F in the dark

cell with grid on grain boundaries

A cell similar to those described above with different grid design was examined. On this cell labeled GBG the grid is printed preferably on grain boundaries¹ of the polycrystalline silicon, as can be seen in figure 4.4.

This cell is of special interest, as the front grid forms closed loops of different diameters, which may exhibit special reaction on external fields.

Contact is made on the grid at a position similar to that of the bus-bars of the H design.



Figure 4.4.
cell GBG

4.2. Industrial Cell

A mono-crystalline silicon cell of type SC14GO-12 produced by Solartec (Czech Republic), with dimensions of 51.45×17.1 mm, this is an area of 8.8 cm^2 , was also investigated. This cell is cut from a bigger cell and thus is not entirely symmetric, as can be seen in figure 4.5. The front grid consists of one bus bar and 14 fingers, half of them 2 mm shorter than the opposite fingers. The back of the cell is entirely metalized. The thickness of the cell is specified with $320 \pm 50 \mu\text{m}$.

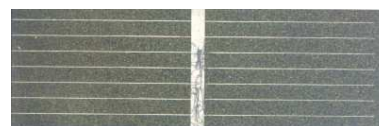


Figure 4.5.
industrial cell SC14GO-12 by
Solartec (under normal
illumination, the front appears
yellow due to interference)

According to the product sheet, the open circuit voltage is about 0.6 V, the short circuit current 0.23 A and its power under standard conditions is 101 mW.

The transparent anti reflection coating, which appears yellow due to interference, solely serves design purposes and is thicker than necessary (188 nm).

The cell is contacted in the same way as the laboratory cells and labeled as sample SC further on.

¹An attempt to enhance efficiency due to the reduction of shadowing losses.

4. Samples

4.3. aSi Thin Film Cell



Figure 4.6.
amorphous silicon cell

An amorphous silicon module is also examined. Its dimensions are 2.9×6.8 cm. As can be seen in figure 4.6 it consists of three cells which are in series connected (see fig. 2.4). A single cell has the dimensions 2.4×2 cm, so the active area of the module is 2.4×6 cm. The whole module has a thickness of 2 mm due to the glass substrate, the amorphous silicon layer can

be expected to be several micrometers thick. An open-circuit voltage of 4.43 V and a short circuit current of 4.5 mA were measured. The maximum power was 14.8 mW, with a curve fill factor of 0.74.

The module, labeled as sample AS, is readily contacted with 1 m of wire, which is rolled up and covered in aluminum foil before connected to the coaxial cable shielding.

4.4. Front-to-Back Contacted Cell

A Front-to-Back contacted cell produced by Q-Cells (Germany) with 22×22 cm² area was also investigated. This cell has an octagonal front grid structure which is connected to the backside of the cell via boreholes (see fig. 4.7). Different from the typical full metallization at the rear side this cell is only contacted spot wise. These spots are connected to five parallel metal stripes, which are collected at the edge of the cell.

The behavior of this cell in an electromagnetic environment is rather difficult to predict theoretically, since various different components interact.

The loops of the front grid may act as loop antennas of several different diameters, while the contact stripes on the back may act as dipole antennas. The back plate with the isolated boreholes may either act as a patch antenna or as an array of high frequency patch antennas formed by the boreholes.

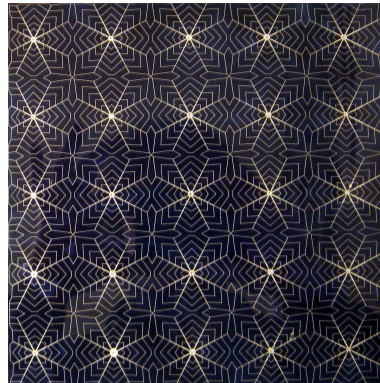


Figure 4.7.
cells with lead-through
contacts

5. Experimental Results

In this chapter the influence of different aspects of solar cells on their behavior in an electromagnetic environment are examined:

- sender receiver geometry
- distance
- size
- pn junction
- back metallization

Additionally comparison with a metal patch is made.

Table 5.1 lists all cells/wafers with their descriptions.

sample	description	size	mm ²
A	no pn-junction, H front grid	100 × 100	
B	no pn-junction, H front grid, back metallization	100 × 100	
E	working cell (bad parameters), H front grid	100 × 100	
F	working cell, H front grid	100 × 100	
GBG	working cell, front grid on grain boundaries	100 × 100	
SC	reduced grid	51.45 × 17.1	
AS	aSi cell	29 × 68	
BC	cell with back contacted front grid	220 × 220	

Table 5.1.
summary of examined cells/wafers

5.1. Sender-Receiver Geometry

Sample E and SC were investigated at different orientations towards the sending antenna. If the dipole is oriented along the x-axis in Cartesian coordinates, 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 (sample E only)

The recorded gain with respect to a reference receiver (see section 3.5.2), for each of these orientations is shown in the figures 5.1 and 5.2.

Sample E

As can be seen in figure 5.1, the cell in plane with the sending antenna, with its fingers aligned with the dipole axis (in the following referred to as parallel alignment), responds most to the external field at low frequencies. The cell in the x-z-plane, which is also in parallel alignment, shows the second best gain, while the other two configurations show a 12 dB weaker reaction. Contrary to the findings of Wada et al. [2005], 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. The very low frequency range (below 1 kHz) will be ignored, as the line frequency resonance distorts the signal.

In the high frequency region the orthogonally oriented cell couples out most power from the sending antenna, followed by the upright parallel cell, while the upright orthogonal and the parallel oriented cells receive about 5 dB less.

Sample SC

In the low frequency region, sample SC converts most radiation when oriented in the x-z plane, at an almost constant gain of -4 dB. The parallel orientation in the x-y shows 2 dB weaker but also constant reaction, while in orthogonal orientation the received radiation decreases with increasing frequency.

As already seen at sample E, orthogonal orientation receives most and parallel orientation least radiation in the high frequency range.

5.1. Sender-Receiver Geometry

The orientation with the highest signal level depends on the sending mode of the antenna. In direct sending mode, parallel orientation leads to the highest reaction, while with amplitude modulation the cells with orthogonal orientation couple out most power. This behavior is not yet understood.

The result suggests that the antenna behavior in the investigated frequency range is rather front grid (assuming dipoles) dominated than area dependent like patch antennas.

5. Experimental Results

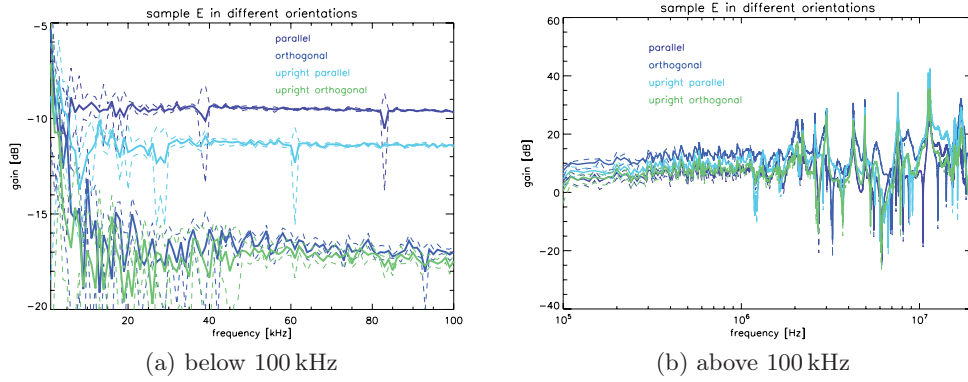


Figure 5.1.
orientation influence:
gain of sample E at different orientations (abscissa in logarithmic scale for
the high frequency range)
dotted lines show the standard deviation

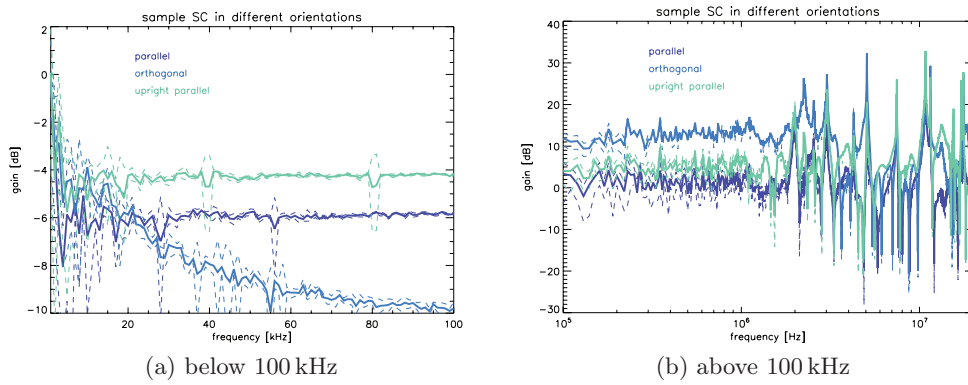


Figure 5.2.
orientation influence:
gain of sample SC at different orientations (abscissa in logarithmic scale for
the high frequency range)
dotted lines show the standard deviation

5.2. Distance Dependence

The dependence of the field strength on distance is shown in figure 5.3 for the reference antenna and samples F, GBG and SC . All distance measurements were made at 50 kHz in direct detection mode.

All recorded points were fitted with the following function:

$$V = A \cdot \sqrt{\frac{1}{k^4 (r - r_0)^6} + \frac{3}{k^2 (r - r_0)^4} + \frac{1}{(r - r_0)^2}} \quad (5.1)$$

where V is the recorded voltage, $k \approx 10.4 \cdot 10^{-6} \text{ cm}^{-1}$ the wavenumber and r_0 the difference between actual distance and distance for best fit, thus $(r - r_0)$ is the effective distance. A contains the remaining parts of the near field function of the Hertz dipole (see eq. 2.7). Since most of them are constants, A is proportional to $I_0 \cdot d$, the product of current on the antenna and dipole arm length (of the DUT).

Samples F and SC are fitted best with the dipole model. Surprisingly, the reference antenna can not be fitted too well and the best fit assumes the antenna 5 cm closer to the sender. Cell GBG has a rather unstable distance behavior, which may be due to its very low voltage level. Anyway it is acceptably well fitted.

Summarized results of the fits can be found in table 5.2.

sample	A	r_0 [cm]
reference antenna	$9.6 \cdot 10^{-8}$	-3.55
F	$2.82 \cdot 10^{-7}$	-0.58
SC	$6 \cdot 10^{-9}$	-1.03
GBG	$3.075 \cdot 10^{-9}$	-5.42

Table 5.2.
parameters of the fits on the distance
dependency

Fits with far field models (which are basically $1/r$ dependent) showed less agreement with the experimental data, which makes the near-field-dipole-model ($1/r^2$ dependent) favorable, which is consistent, since the distance is very small compared to the wavelength.

5. Experimental Results

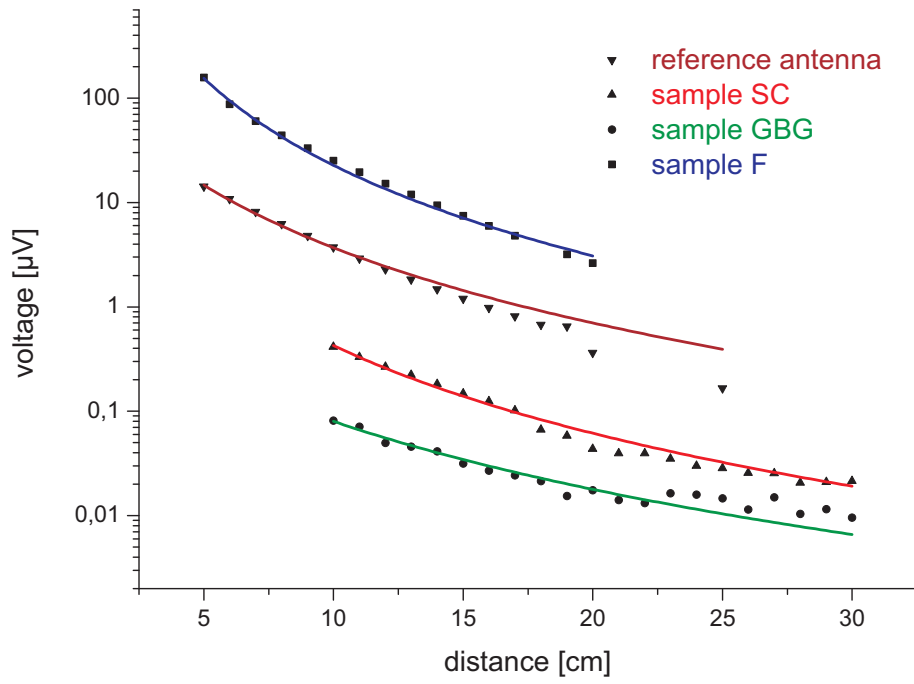


Figure 5.3.
received signal voltage versus distance for the reference antenna (triangle down), an sample SC (triangle up), sample F (square) and sample GBG (circle)
lines show results of the fit according to equation 5.1

5.3. Size Influence

For the examination of size dependent effects, samples F, SC and BC were compared. While sample F measures $10 \times 10 \text{ cm}^2$, sample SC measures $5.1 \times 1.5 \text{ cm}^2$ and sample BC $22 \times 22 \text{ cm}^2$. The distance between sample and antenna was measured from the center of the sample to the antenna. The orientation of the samples was parallel to the antenna in the x-y-plane.

The recorded voltage level (see section 3.5.1) for the DUTs can be seen in figure 5.4.

At low frequencies sample F and sample BC show a linear increase of the voltage level with the logarithm of the frequency. The signal of sample SC is about 20 dBV weaker than that of sample F and has a higher uncertainty due to its low level. At sample BC a constant voltage level of -83 dBV was measured from 1 kHz to 60 kHz followed by an increase of 6 dBV.

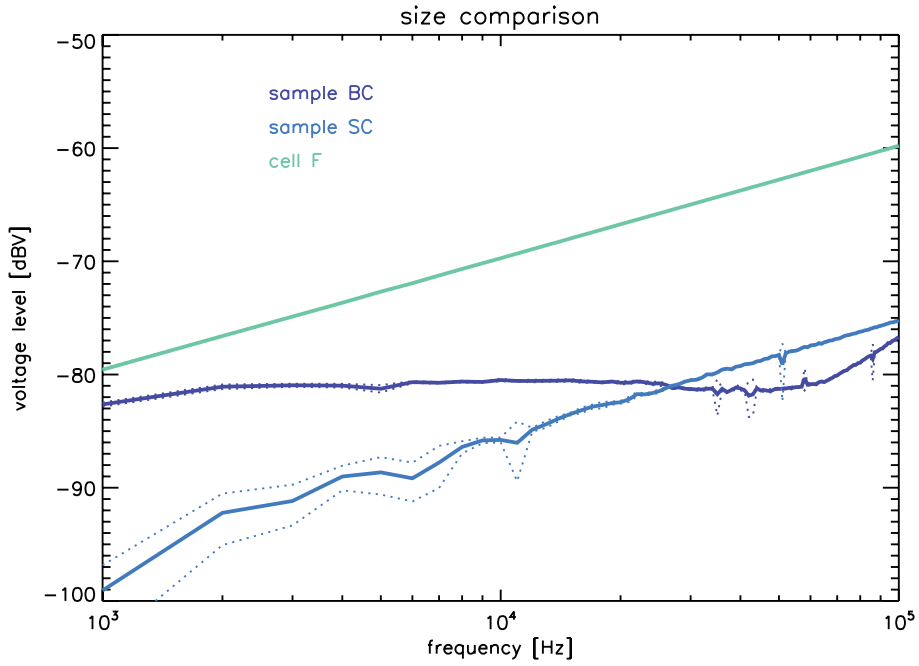
Above 100 kHz spikes appear for all samples but seldom at the same frequency. The signal strength increase is very similar for all samples and their level differences remain fairly constant: the difference between sample SC and sample F is $\approx 7 \text{ dBV}$, for sample BC and sample F $\approx 12 \text{ dBV}$.

Dividing the measured signal of the samples through their size results in an amplitude per square millimeter of 7.6 pV/mm^2 for sample BC and 6.7 pV/mm^2 for sample SC which is quite similar. Sample F has only 3.2 pV/mm^2 which is significantly weaker but still in the same order of magnitude.

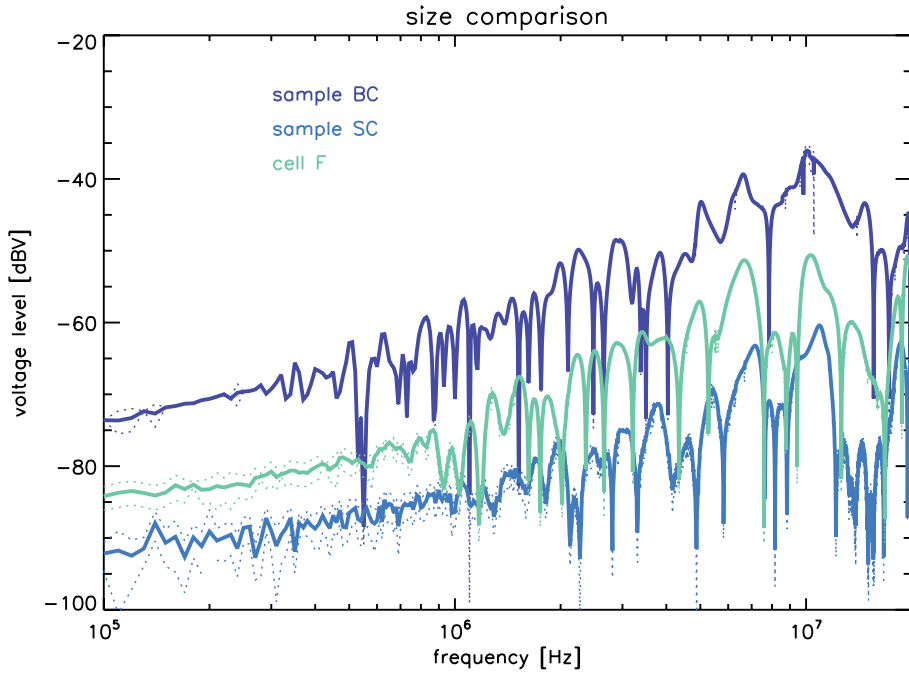
While sample F has 2×19 dipoles on 100 mm length, that is a line density of 1.9 cm^{-1} , sample SC has seven dipoles on 17.1 mm length, respectively a line density of 4.1 cm^{-1} . In both cases each dipole has a height of $\approx 48 \text{ mm}$. Comparison of the line density with the amplitude per area shows that sample F which has half the line density of sample SC also has half the amplitude per square millimeter.

Generally the signal level of a sample is proportional to its size. While the good agreement of amplitudes per square millimeter for samples SC and BC favors the patch antenna model, the introduction of a dipole line density explains the difference between sample F and sample SC.

5. Experimental Results



(a) below 100 kHz



(b) above 100 kHz

Figure 5.4.
size effects: voltage levels of samples F and SC
dotted lines show the standard deviation

5.4. pn-Junction Influence

The influence of the presence of a pn-junction is examined by comparing the gain of samples B and F (figure 5.5). Both samples are based on the same type of polycrystalline silicon, have an H-front grid and full back metallization. Only cell F has been processed to form a pn-junction. The signal of the cells was measured without bias voltage and in the dark.

At low frequencies, the influence of the pn junction is negligible, since it leads in this comparison to a gain reduction of 0.7 dB in the absence of a pn-junction (see fig. 5.5a). At higher frequencies, the difference is higher, but within the uncertainty range of the measurements (fig. 5.5b). Above 1 MHz cell F is slightly more reactive, its curve showing more spikes than that of sample B.

Under the conditions used in the experiment, the influence of the pn junction on the reception of electromagnetic radiation is mostly below the detection limit.

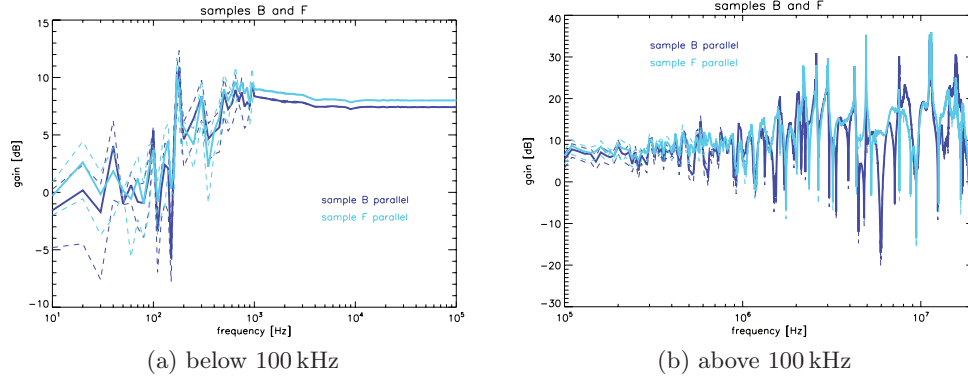


Figure 5.5.
pn junction influence:
gains of samples B and F
dotted lines show the standard deviation

5. Experimental Results

5.5. Back Metallization

The comparison of samples A and B shows the influence of the back metallization on the behavior in an electromagnetic environment. Both samples have an H-grid on its front, but no pn-junction. Only sample B has a back metallization.

In the dipole model this may be explained with a larger directivity of the antenna array in z-direction. Consequently, the radiation received from the y-direction would be less. This effect would be very small in the examined frequency region, but should be frequency dependent. Measurements on cells in different orientations in section 5.1 do not give a validation since sample SC receives more radiation in upright orientation, but sample F receives less.

In figure 5.6 it can be seen that the samples produce very similar curves, only the curve of sample B is approximately 0.5 dB weaker.

It is more probable that the lower gain is an effect of the cell contact. Small inhomogeneities in the screen printed grid reduce the conductivity of the contact between steel tip and the grid and thus lower the recorded voltage.

In the examined frequency range, no influence of the back metallization on the behavior in an electromagnet ambiance was observed.

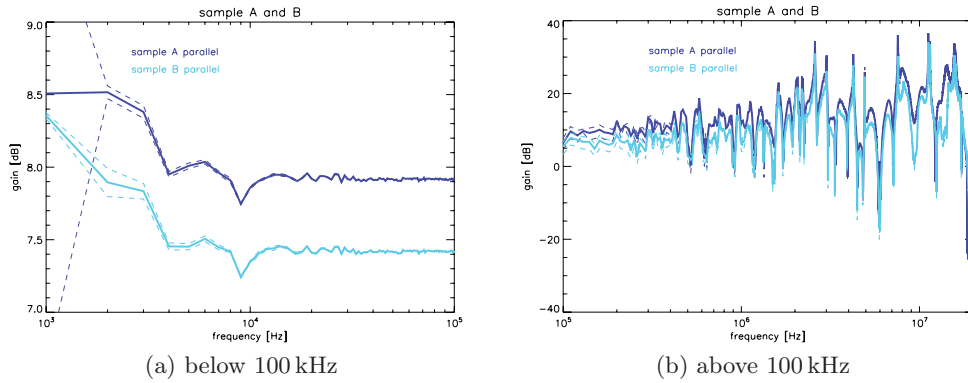


Figure 5.6.
back metallization:
gains of samples A (no back metallization) and B
dotted lines show the standard deviation

5.6. High Frequency Range

Although the high frequency regime is disturbed by the position dependent reflections in the compartment, some of the peaks and dips are characteristic for the DUT. Figure 5.7 shows a comparison of different samples in the range from 5 – 20 MHz.

First, samples F and GBG will be compared, which have the same dimensions and where roughly at the same position in the compartment during measurement. Both samples behave similarly between 9 – 20 MHz, showing a slow decrease in signal from 9 MHz on, which ends in a dip at 16.5 MHz (this dip can be found for all cells), from where on intensity increases for both and has another dip at 19 MHz.

Comparing sample SC with sample AS, which has about thrice the area, a comparable behavior can be found from 5 – 11 MHz and from 16.5 – 20 MHz. In the range from 12 – 16.5 MHz, the curve of sample SC show various dips and is noisy.

In summary, differences in the high frequency range are mostly dependent on the size of the DUTs.

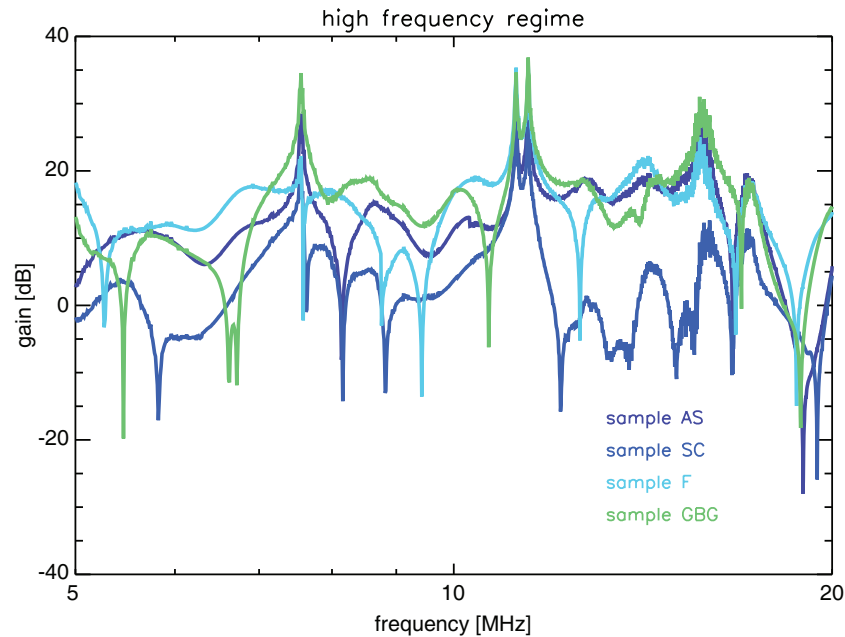


Figure 5.7.
high frequency regime of various cells

5.7. Comparison with Patch

Samples SC and F are compared with copper covered hard paper with the same dimensions. While the upper side of these plates is copper coated, its backside is contacted with adhesive copper foil.

Both figures 5.8 and 5.9 show good agreement between the solar cell and its equivalent patch. For sample SC, the difference is not more than 2 dB in the examined range. For sample F it is only about 0.1 dB in the low frequency region, while above 100 kHz bigger differences appear. The patch shows a smaller gain and peaks shifted relative to those of sample F.

The patch antenna model predicts a significant change in field strength if the substrate thickness is changed. The hard paper has a relative permittivity of approximately 4.5 and is 1.5 mm thick. This leads to a theoretical resonance frequency of 680 MHz for the bigger patch, while cell F has a theoretical resonance frequency of 430 MHz. A slightly different signal increase of the patch compared to the cell would have been expected but was not found.

Summarizing, it can be said that the antenna capabilities of solar cells are roughly similar to those of copper covered hard paper. The thickness of the patches is of minor importance in the applied frequency range. Corrections following the dipole model may be necessary depending on the cell architecture.

5.7. Comparison with Patch

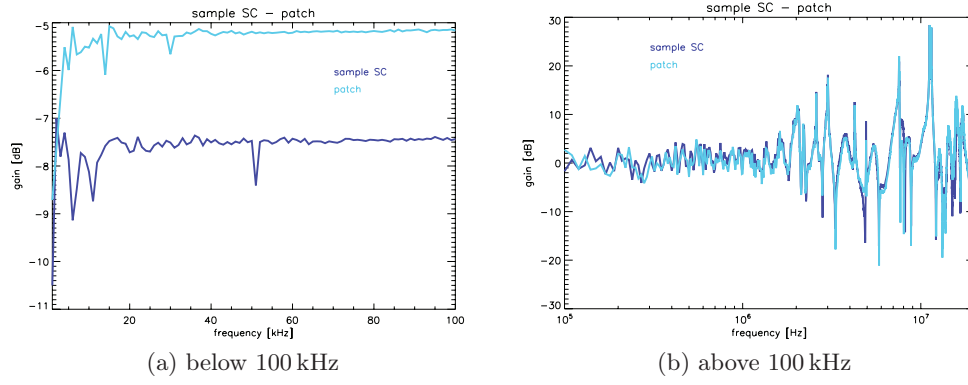


Figure 5.8.
voltage levels of sample SC and an equally sized patch

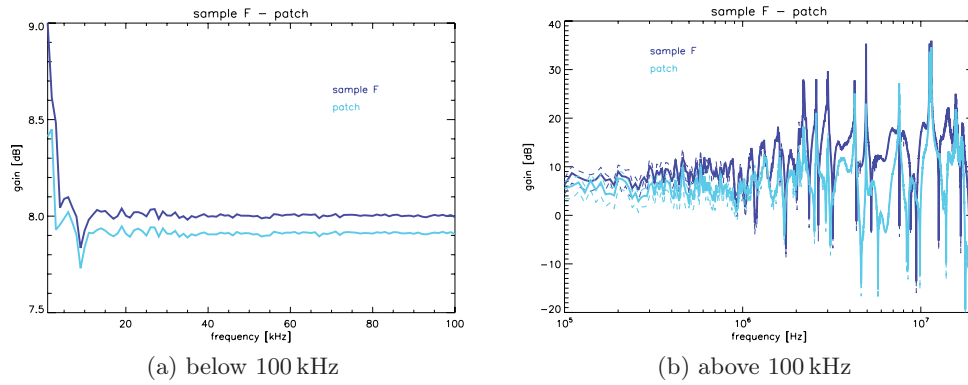


Figure 5.9.
voltage levels of sample F and an equally sized patch

5. *Experimental Results*

6. Conclusions

Measurements on different poly- and mono-crystalline silicon solar cells as well as on an amorphous silicon solar cell have been made in the frequency range from 10 Hz to 20 MHz and the recorded spectra were compared with theoretical predictions derived for patch antennas and dipole antenna arrays. Geometrical as well as architectural parameters have been examined.

Comparison of the signal levels of cells in different orientation towards the sending antenna showed that the orientation with the highest signal level depended on the sending mode of the antenna. In direct sending mode, parallel orientation led to the highest reaction, while with amplitude modulation the cells with orthogonal orientation coupled out most power. This behavior is not yet understood. The higher signal level in parallel orientation suggests that the antenna behavior in the investigated frequency range is rather front grid (assuming dipoles) dominated than area dependent like patch antennas.

The signal levels of different cells at a frequency of 50 kHz at distances ranging from 1 cm to 20 cm have been fitted with far and near field models. The far field models (which are basically $1/r$ dependent) showed less agreement with the experimental data, which makes the near-field-dipole-model ($1/r^2$ dependent) favorable. This is consistent, since the distance given by the experimental setup is very small compared to the wavelength.

Examination of the size dependency of the signal level showed that generally the signal level of a sample is proportional to its size. While the good agreement of amplitudes per square millimeter for some samples favors the patch antenna model, the introduction of a dipole line density is necessary to explain the different levels of other samples.

Without external bias voltage and in the dark, the influence of the pn junction on the reception of electromagnetic radiation was mostly below the detection limit.

Comparison of partly processed wafers showed no influence of the back metallization on the behavior in an electromagnetic ambiance in the examined frequency range.

Closer examination of the high frequency range of the DUTs showed that differences in that range are mostly dependent on the size of the DUTs.

Due to architectural similarities between solar cells and patch antennas, their gain was compared to the gain of equally sized copper covered hard paper samples. It

6. *Conclusions*

was found that the antenna capabilities of the investigated solar cells are roughly similar to that of copper covered hard paper. The thickness of the patches is of minor importance in the applied frequency range. Corrections following the dipole model are necessary for some depending on the cell architecture.

Summarizing, solar cells and modules absorb significant amounts of low frequency electromagnetic radiation at distinct frequency bands. Absorbed electromagnetic noise may be delivered to the power conditioning units and cause further problems, depending on the installation. Small scale standalone applications make little use of power electronics, thus most noise would be absorbed by the high capacitance of the storage accumulators. Since engineer standards only cover certain frequency ranges for grid connected devices, it can be assumed that absorbed noise may either cause damage to these electronics or may pass unfiltered into the electricity grid.

Following the reciprocity theorem, noise from external sources introduced into a photovoltaic power generator may also be emitted from the devices. Given the size of installed generators emitted radiation may easily reach unacceptably high levels. Further investigations of the electromagnetic emission and absorption of photovoltaic power generator is necessary for the design of reliably electromagnetic interference compatible devices.

Bibliography

- Christian Bendel, Wolfgang Enders, Thomas Degner, Norbert Henze, Jörg Kirchhof, Gerald Klein, Holger Lange, Celine Trousseau, Christian Halter, Peter Scheibenreiter, Peter Wurm, Peter Claus, Carsten Metzger, Armin Schülbe, Hans Daub, and Katharina Stanley. Emc and safety design for photovoltaic systems. Technical report, ISET e. V., Kassel, Germany, 2002.
- Kai Chang. *Handbook of RF/microwave components and engineering*. John Wiley & Sons, Hoboken, New Jersey, 2003.
- Christos G. Christodoulou and Parveen F. Wahid. *Fundamentals of Antennas: Concepts and Applications*. SPIE - The International Society for Optical Engineering, 2001.
- Vincent F. Fusco. *Foundations of antenna theory and techniques*. Prentice Hall, 2004.
- Ramesh Garg and Inder Bahl. *Microstrip Antenna Design Handbook*. Artech House, 2000.
- Adolf Goetzberger and Volker U. Hoffmann. *Photovoltaic Solar Energy Generation*. Springer, 2005.
- G. Kumar and K.P. Ray. *Broadband Microstrip Antennas*. Artech House, Inc., 2003.
- Punit Shantilal Nakar. Design of a compact microstrip patch antenna for use in wireless/cellular devices. Master’s thesis, Florida State University, 2004. URL <http://etd.lib.fsu.edu/theses/available/etd-04102004-143656/>.
- Jenny Nelson. *The Physics of Solar Cells*. Imperial College Press 57 Shelton Street Covent Garden London, 2003.
- Paul A. Tipler. *Physik*. Spektrum Akad. Verlag, 2000.
- Tomoyuki Wada et al. Radiated electromagnetic field from a solar cell for cispr radiated emission measurement method. *International Symposium on Electromagnetic Compatibility*, 1:112–117, 2005.
- Hans Wagemann and Heinz Eschrich. *Grundlagen der photovoltaischen Stromwandlung*. Teubner, 1994.
- Wikipedia. Spherical coordinate system — wikipedia, the free encyclopedia, 2009. URL http://en.wikipedia.org/w/index.php?title=Spherical_coordinate_system&oldid=327708557. [Online; accessed 6-December-2009].

Bibliography

A. Addendum

A.1. Symbols

name	symbol	units
current density	$\mathbf{j}$	A/m ²
angular velocity	ω	1/s
wavenumber	k	1/m
radiation pattern	ψ	V
electric field	$\mathbf{E}$	V/m
magnetic field	$\mathbf{H}$	A · m
power	P	W
power radiation pattern	G	dB
directivity gain	G_D	dB
dipole moment	$\mathbf{p}$	C · m
wavelength	λ	m
distance between antennas	D	m
dipole arm length	d	m
current	I	A
dipole diameter	a	m
impedance	Z	Ω
patch antenna width	W	m
patch antenna length	L	m
patch antenna height	h	m
permittivity	ϵ	F/m
relative permittivity	ϵ_r	-
frequency	ν	Hz
radiation resistance	R_r	Ω
voltage	U	V

A. Addendum

A.2. Constants

name	symbol	value	units
speed of light	c	299792458	m/s
permittivity of free space	ϵ_0	$8.854187817 \cdot 10^{-12}$	F/m
vacuum permeability	μ_0	$4 \cdot \pi \cdot 10^{-7}$	H/m
free space impedance	$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}$	376.7303	Ω

B. curriculum vitae

Name: Markus Drapalik
Date of birth: August 11th, 1984
Place of birth: Vienna, Austria

Diploma thesis: The Reaction of Photovoltaic Power Generators to External
Electromagnetic Radiation
Advisor: Wolfgang Lang

Oct. 2003 - present: studies in Physics at the Faculty of Physics, University of Vienna
Oct. 2002 - Sept. 2003: Civilian service at the Otto Wagner Spital, Vienna
June 2002: Matura (school leaving examination)
1994 - 2002: Gymnasium und Realgymnasium Parhamerplatz
1990 - 1994: Volksschule Landsteiner-gasse

B. curriculum vitae

C. Abstract - English

The Reaction of Photovoltaic Power Generators to External Electromagnetic Fields

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 have been installed and are planned in the European Union. These consist of multiple solar trackers on which several square meters of solar modules are mounted. The development of solar cells and modules adapted for building integrated photovoltaics (BIPV) results in large areas covered with interconnected solar modules. It can be said that photovoltaic power generators with an active area of over 1000 m^2 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 electronic and the power grid, yet unknown problems of electromagnetic compliance may arise.

This diploma thesis takes a qualitative look at the reaction of photovoltaic cells to external electromagnetic fields of low frequency. Different cells were investigated in a frequency range of 10 Hz to 20 MHz and the influence of various design parameters is discussed.

Two theoretical models for the description of the antenna behavior of solar cells are presented, the dipole model and the patch antenna model. The first describes the solar cell's front grid as a dipole antenna array, while the second assumes a homogeneously conducting front side, in which case the cell resembles a patch antenna. Experimental findings suggest that both models are necessary to find a satisfying description.

Measurements showed that the size of the cells is the most significant parameter, since the voltage level scales almost linearly with the cell area. For some samples the additional consideration of the line density of the front grid is necessary. Likewise, the voltage level depends on the orientation of the cells towards the sending antenna while other design parameters such as pn-junction and back metallization had little effect on the gain.

C. Abstract - English

D. Abstract - German

Die Reaktion photovoltaischer Stromgeneratoren auf externe elektromagnetische Felder

Zunehmendes Interesse und staatliche Förderungen führten zu exponentiellem Wachstum der installierten Kapazität photovoltaischer Stromgeneratoren. Zahlreiche Solarparks innerhalb der Europäischen Union wurden bereits installiert oder sind in Planung. Diese bestehen aus mehreren Solar Trackern auf denen jeweils einige Quadratmeter Solarmodule installiert sind. Die Entwicklung von Solarzellen und -modulen für die gebäudeintegrierte Photovoltaik (BIPV - building integrated photovoltaics) führt zu großen Flächen die mit elektrisch verbundenen Solarmodulen bedeckt sind. Daher kann davon ausgegangen werden, dass photovoltaische Stromgeneratoren mit einer aktiven Fläche von über 1000 m^2 keine Seltenheit mehr darstellen.

In Anbetracht der großen Flächen, die mit elektronischen Geräten mit komplexem Verhalten unter Wechselstrom - das noch nicht vollständig erforscht ist - bedeckt sind, kann eine Reaktion auf äußere elektrische Felder erwartet werden. Da diese Geräte an das öffentliche Stromnetz angebunden sind muss mit bisher unbekannten Schwierigkeiten im Bereich der elektromagnetischen Verträglichkeit gerechnet werden.

Diese Diplomarbeit dient der qualitativen Betrachtung der Reaktion photovoltaischer Zellen auf niederfrequente äußere elektrische Felder. Verschiedene Zellen wurden in einem Frequenzbereich von 10 Hz bis 20 MHz untersucht und der Einfluss mehrerer Designparameter wird betrachtet.

Zwei Modelle zur Beschreibung der Antenneneigenschaften von Solarzellen werden vorgestellt, das Dipol- und das Patch-Antennen-Modell. Während ersteres das Frontgrid einer Solarzelle als Dipolantennenarray beschreibt, wird im zweiten eine homogen leitfähige Zellvorderseite angenommen, womit die Zelle im Wesentlichen einer Patchantenne entspricht. Die experimentellen Ergebnisse sprechen dafür, dass beide Modelle für eine zufriedenstellende Beschreibung notwendig sind.

Die durchgeführten Messungen weisen die Zellgröße als signifikanten Parameter aus, da der Spannungspegel sich linear mit der Zellfläche verändert, wobei für

D. Abstract - German

einige Proben die Liniendichte des Frontgrids zusätzlich berücksichtigt werden muss. Weiters hängt der Spannungspegel von der Orientierung der Zellen zur Sendeantenne ab, während andere Designparameter wie pn-Übergang oder Rückseitenmetallisierung kaum Effekt auf den Antennengewinn der Zellen haben.