

Tijdschrift van het NERG

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DE VERENIGING NERG

Het NERG is een wetenschappelijke vereniging die zich ten doel stelt de kennis en het wetenschappelijk onderzoek op het gebied van de elektronica, signaalbewerking, communicatie- en informatietechnologie te bevorderen en de verbreiding en toepassing van die kennis te stimuleren.

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De jaarlijkse contributie bedraagt voor gewone leden € 43,- en voor studentleden € 24,-. Bij automatische incasso wordt € 2,- korting verleend.

Gevorderde studenten aan een universiteit of hogeschool komen in aanmerking voor het studentlidmaatschap. In bepaalde gevallen kunnen ook andere leden, na overleg met de penningmeester voor een gereduceerde contributie in aanmerking komen.

HET TIJDSCHRIFT

Het tijdschrift verschijnt drie maal per jaar. Opgenomen worden artikelen op het gebied van de elektronica, signaalbewerking, communicatie- en informatietechnologie. Auteurs, die publicatie van hun onderzoek in het tijdschrift overwegen, wordt verzocht vroegtijdig contact op te nemen met de hoofdredacteur of een lid van de Tijdschriftcommissie.

Voor toestemming tot overnemen van (delen van) artikelen dient men zich te wenden tot de tijdschriftcommissie. Alle rechten berusten bij de auteur tenzij anders vermeld.

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INHOUD

inhoud	
Van de redactie	2
<i>Michel Arts</i>	
Ring resonator-based integrated photonic beam former for phased array antennas . . .	3
<i>Leimeng Zhuang, David Marpaung, Maurizio Burla, Reza Khan, and Chris Roeloffzen</i>	
A novel astronomical application for formation flying small satellites	8
<i>M.J. Bentum, C.J.M. Verhoeven, A.J. Boonstra, A.J. van der Veen, E.K.A. Gill</i>	
Double Solenoid ELF Magnetic Field Exposure System for In-Vitro Studies	16
<i>C. Sismanidou, A. C. F. Reniers, A. P. M. Zwamborn</i>	
Proefschriftenoverzicht 2008-2010	24
PAO-cursusaanbod 2012 . . .	40



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Van de redactie

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Nu het einde van het jaar nadert is dan toch eindelijk het eerste nummer van 2011 van ons tijdschrift verschenen. Zoals ik al vaker op deze plaats genoemd heb, is het moeilijk om kopij te vinden. De vraag dringt zich dan op waar dat dan aan ligt. Een mogelijke oorzaak ligt in het beperkte bereik van ons tijdschrift. Iedereen heeft het tegenwoordig druk en als je als onderzoeker wil publiceren kies je toch eerder voor een IEEE-tijdschrift dan voor het Tijdschrift van het NERG.

Vorig jaar bestond het NERG 90 jaar. In het volgende nummer zal hier aandacht aan besteed worden. Onze oud-voorzitter Wim van Etten is bezig met een artikel over de geschiedenis van het NERG. Verder willen we in

het volgende nummer een register van gepubliceerde artikelen in ons tijdschrift publiceren. Het laatste register is in 1995 gepubliceerd ter gelegenheid van het 75-jarig jubileum van het NERG. We moeten nog bekijken of dit een integraal register wordt met alle publicaties sinds 1920 of dat het een register wordt met alleen de publicaties vanaf 1995.

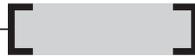
In dit nummer vindt U een artikel over geïntegreerde optische beamformers m.b.v. ring resonatoren. Optische beamforming kan toegepast worden voor de fasesturing van phased-array antennes voor bijv. radar en radio-astronomie. Verder een artikel over OLFAR. OLFAR is een concept voor een radiotelescoop werkend in het frequentiegebied

1-30 MHz. Deze radiotelescoop zal bestaan uit 50 satellieten in de ruimte. Het laatste artikel gaat over het ontwerp van een dubbelpoel voor in-vitro biologische experimenten. Verder treft U ook weer het vertrouwde proefschriftenoverzicht aan. Omdat dat vorig jaar niet gepubliceerd is, treft U nu het overzicht van de jaren 2008-2009 en 2009-2010 aan. Vanaf volgend jaar zullen de proefschriftenoverzichten voortaan per kalenderjaar gepubliceerd worden omdat dit beter aansluit bij de overzichten die de universiteiten zelf maken. Het volgende proefschriftenoverzicht zal, als overgang, de periode 1 september 2010 - 31 december 2011 omvatten.



Ring resonator-based integrated photonic beam former for phased array antennas

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Introduction

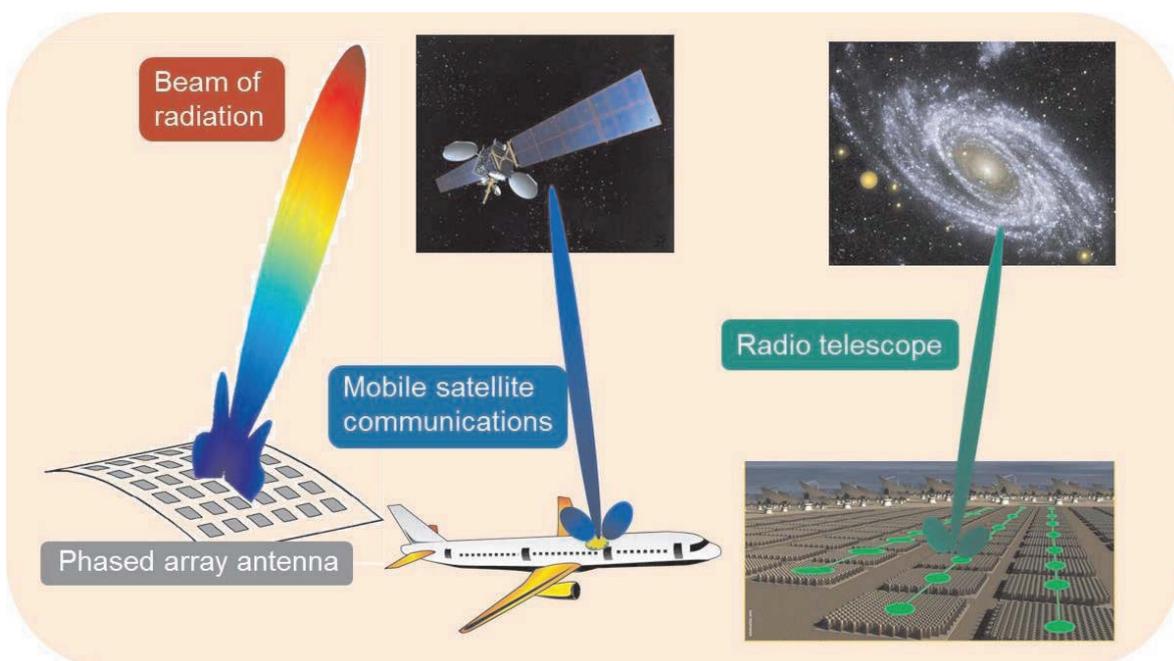
In this article we introduce one of the microwave photonics techniques being researched in our group, namely integrated photonic beam former for phased array antennas. The photonic beam former operates with true time delays achieved by means of integrated optical ring resonator filters. Compared to the conventional electrical beam former, this photonic solution provides the advantages of large instantaneous bandwidth, small size, light weight, low loss, and immunity to electromagnetic interference. The bandwidth configurability and continuous delay tunability of the optical ring resonator-based delay elements allow the

phased array antenna to perform squint-free and seamless beam steering for broadband applications such as mobile K_u-band satellite communication and gigahertz-bandwidth radio telescope. An exhaustive system performance analysis and the characterization of a realized photonic beam former chip have been published in [1] and [2], which are later referred to as the breakthroughs in microwave photonics in 2010 [3].

Phased array antenna

Phased array antennas consist of multiple identical antenna elements which are spaced orderly from each other. With the proper design of the antenna

Figure 1: Schematic of beamforming and two applications of phased array antenna.



element and the array geometry, the radiation pattern of a phased array antenna can be realized with strong sensitivity of direction. This allows intentionally reinforced transmission and reception of RF signals in the target-communication directions and at the same time signal suppression in the directions causing interference as illustrated in Figure 1. This functionality is achieved by means of the beamforming technique. Unlike other types of direction-sensitive antennas such as dish antennas and horn antennas, a phased array antenna can steer its formed beam electrically without the need of being attached on a mechanical rotator. This grants the phased array antenna attractive properties such as high steering accuracy and speed, low profile, and light weight. Nowadays phased array antennas play an important role in modern radar and wireless communication systems. Conventional phased array antennas are fed by the electrical phase shifter-based beam former, which is a circuitry to control the amplitude and phase of each antenna element. However, it suffers from the well-known beam squint problem (beam direction varies with RF frequency), limiting the antenna to narrowband operations. For many applications, however, it is highly desirable that the phased array antennas can operate in a broad band, such as K_u -band (10.7 - 12.75 GHz) antennas for satellite communications and gigahertz-bandwidth antenna telescopes for radio astronomy. An effective solution to the problem is the use of true time delays instead of the phase shifters. Traditionally, the beam formers for the phased array antennas were realized using individual electrical and electronic components. This was the most intuitive approach since antennas operate on an electrical driving source. With the advancement of technology, severe limitations were observed in some electrical devices. For example, copper wires display high losses at high frequencies resulting in a limited bandwidth for the feed signals. Furthermore, beam formers using traditional electronic components are usually bulky and have a relatively high weight, thus limiting their use in airborne systems. Integrated electronic beam formers features small size and light weight. However, desired properties such as multi-gigahertz bandwidth, low loss, large delay range, continuous tunability, and low channel crosstalk caused by electromagnetic interference still remain challenges, and in general the improvements of them are hindered by the physical limits of electronics. However, another technology field, microwave photonics, opens the door

of overcoming the physical limits of the current electronics in RF/microwave systems by means of the utilization of photonic devices.

Optical beam former

Microwave photonics is a relative young and interdisciplinary research area. It investigates the techniques of processing RF/microwave signals with photonic devices, motivated by the attractive advantages of photonic devices, such large instantaneous bandwidth, light weight, small size, low loss, and immunity to electromagnetic interference. In the recent years microwave photonics has successively found itself in the applications such as broadband wireless access networks, sensor network, radar, satellite communications, instrumentation, and warfare systems, and currently there is an increasing effort in researching new microwave photonics techniques for the generation, processing, control and distribution of microwave and millimeter-wave signals. Among them an interesting subject is true time delay-based optical beam former for phased array antennas. True time delay-based optical beamforming techniques can be classified into two categories: free-space optics-based beam formers and optical beam formers using fiber or guided-wave optics. The first category involves bulky optic components (mirrors, lenses, prisms, and etc.) and normally has a relatively large size and heavy weight. The second category is highly preferred for the realization of light and compact systems. The optical delay line structures that have been proposed as the true time delay elements of the optical beam former include optical fibers, fiber Bragg gratings, semiconductor optical amplifier, and integrated photonic filters. Among them integrated optical ring resonator (ORR) filters appear to be an outstanding candidate for tunable delays. Beside their compactness, simplicity in realization and operation, ORR filters provide continuous delay tunability over a configurable bandwidth [4]. Therefore, the ORR-based integrated photonic beam former not only shares the common advantages of microwave photonics but also allows the phased array antenna to perform squint-free and seamless beam steering for broadband applications.

Device principles

When an optical carrier is modulated by an RF signal and propagates through an ORR filter, the effective time delay to the RF signal is determined by the group delay of the filter, the simplest imple-

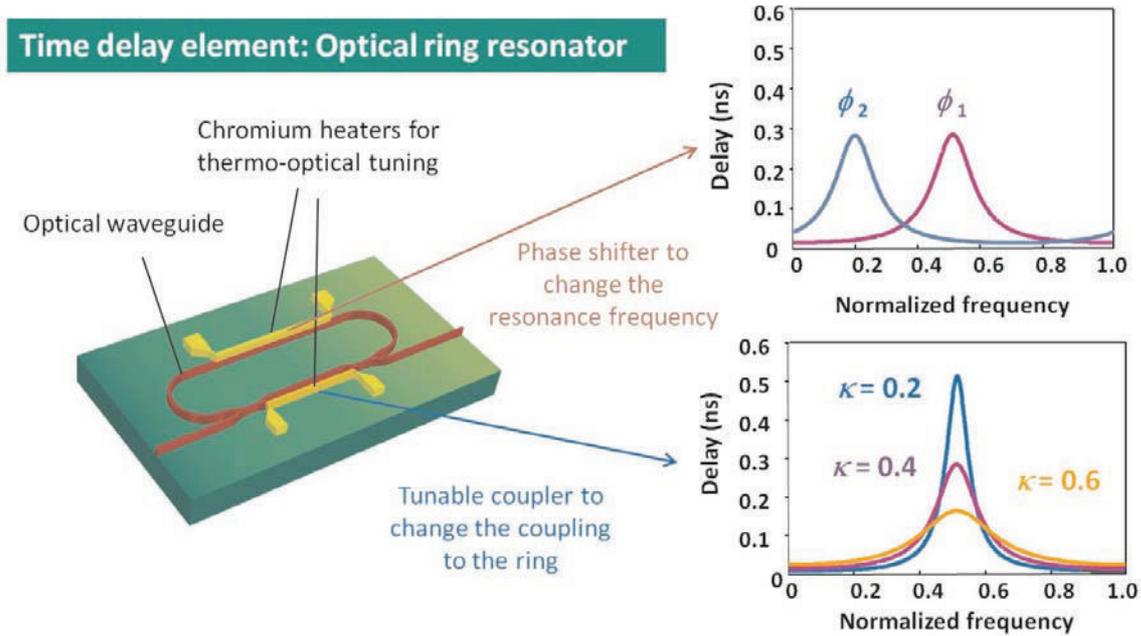
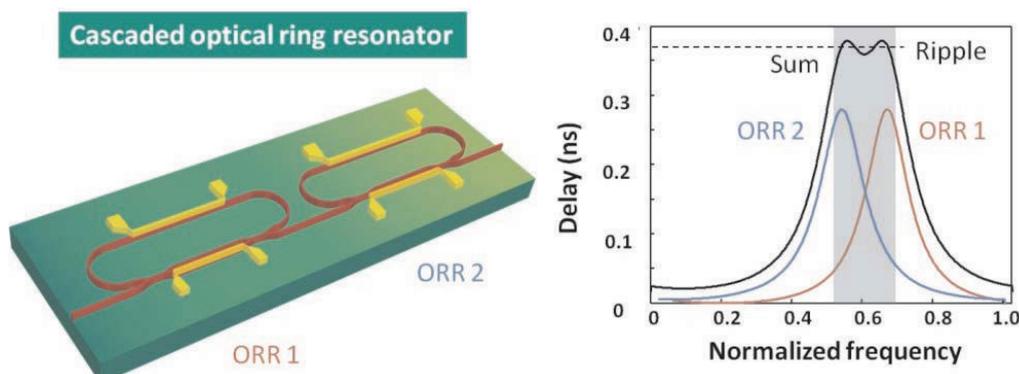


Figure 2: Tunable optical delay based on an optical ring resonator. The group delay response of such an ORR is a bell-shaped function of the frequency, where its resonance frequency and maximum delay can be tuned using thermo-optical tuning mechanism.

mentation of which is a ring-shaped waveguide placed in parallel to a straight waveguide, as illustrated in Figure 2. The group delay response is periodic and the periodicity (dubbed as the free spectral range) is inversely proportional to the round-trip time in the ring. Each period of the group delay response is a symmetric bell-shaped function of frequency, centered at the resonance frequency of the ring (Figure 2). This resonance frequency can be varied by tuning the round-trip phase shift, ϕ , of the ring and the maximum delay can be tuned by varying the power coupling coefficient between the straight waveguide and the ring, κ . In our solution, the ORRs are realized in an integrated chip and the thermo-optical tuning mechanism is used to vary the resonance frequency

and the coupling coefficient of the ORR. In the chip each ORR uses two chromium heaters for the tuning, as illustrated in Figure 2. The principle of this thermo-optical tuning can be found in [5]. The peak value of the delay is approximately inversely proportional to the width of curve since the area underneath the delay curve in one period is always equal to one. This imposes a trade-off between the highest delay values that can be provided with the bandwidth. To overcome this, several ring resonators can be cascaded, where the total group delay response is the sum of the individual ring responses. This is illustrated in Figure 3. When the optical ring resonators are placed in the paths of a signal combining circuitry for the phased array antenna, an optical beamforming network (OBFN)

Figure 3: Left: schematic of two serial ORRs, right: group delay response of a cascade of two ORRs is the sum of the group delay responses of the individual ORR. In this way, the maximum delay and the bandwidth of the response can be increased.



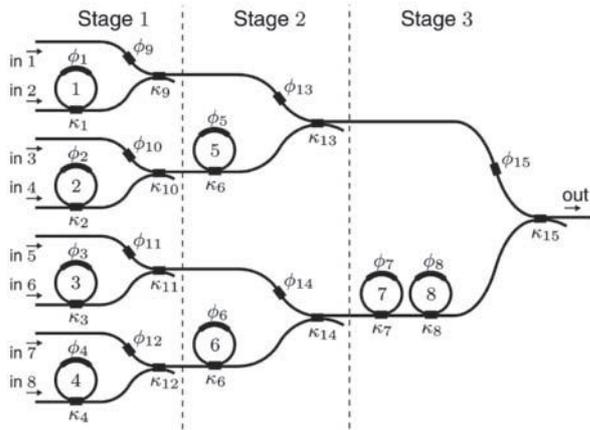


Figure 4: Schematic of an ORR-based optical beam forming network

is obtained as depicted in Figure 4. The amplitude tapering for the beamforming of the phased array antenna is achieved by employing tunable coupler-based combiners in the signal combining circuitry.

System architecture

On the system level, advanced signal processing techniques, namely filter-based optical single-sideband suppressed-carrier modulation and balanced coherent optical detection are used in our solution for the E/O and O/E conversion of the signals. The optical single-sideband suppressed-carrier modulation significantly reduces the optical bandwidth requirement on the OBFN. As explained in the previous section, this bandwidth reduction means the reduction of the required number of ORRs and hence the reduction of OBFN complexity. Moreover, balanced optical detection effectively cancels out the undesired DC and second-order components in the detector output, which improves the signal dynamic range of the system [1], [2]. As another advantage the required

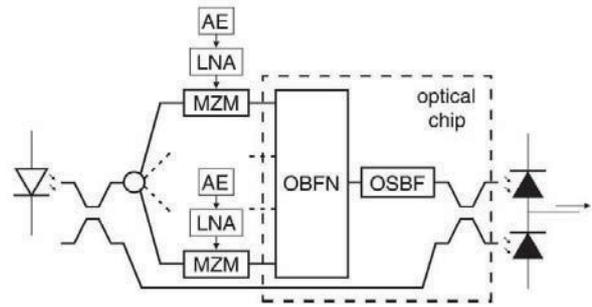
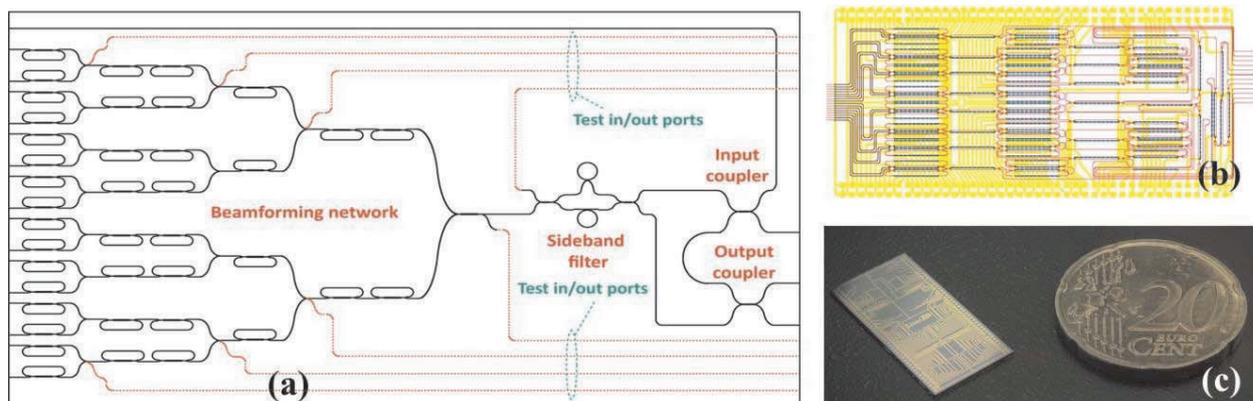


Figure 5: Architecture of photonic beam former system (AE: antenna element, LNA: low noise amplifier, MZM: Mach-Zehnder modulator, OSBF: optical sideband filter)

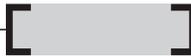
optical sideband filter and the optical carrier reinsertion circuitry can be achieved with the same building blocks as the beamforming network and therefore can be integrated together with it in one single photonic chip. The architecture of the photonic beam former is depicted in Figure 5. Recently, such a photonic beam former chip has been designed and fabricated for research purpose. It consists of a 16×1 binary-tree combining circuitry with a total of 40 ORRs symmetrically allocated in the optical paths, an optical sideband filter consisting of a double-ring assisted Mach-Zehnder interferometer [6], and an optical carrier reinsertion circuitry. It is able to provide a maximum delay of 290 ps over an optical bandwidth of 4.5 GHz, and the footprint of the chip is $2 \times 1 \text{ cm}^2$. The schematic of this photonic beam former chip is depicted in Figure 6a. The chip has been realized on a silicon substrate by LioniX B.V. using their proprietary TriPleX™ planar waveguide technology [7], which features low fabrication cost, low propagation loss, and compact footprint. The chip mask layout and a photograph of the fabricated chip are shown Figure 6b and 6c, respectively.

Figure 6: Photonic beamformer chip. (a) Schematic of the beamformer chip. (b) Mask layout of the beamformer chip. (c) Photograph of a fabricated beamformer chip.



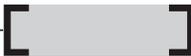
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A novel astronomical application for formation flying small satellites

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OLFAR, Orbiting Low Frequency Antennas for Radio Astronomy, will be a space mission to observe the universe frequencies below 30 MHz, as it was never done before with an orbiting telescope. Because of the ionospheric scintillations below 30 MHz and the opaqueness of the ionosphere below 15 MHz, a space mission is the only opportunity for this as yet unexplored frequency range in radio astronomy. The frequency band is scientifically very interesting for exploring the early cosmos at high hydrogen redshifts, the so-called dark-ages and the epoch of reionization, the discovery of planetary and solar bursts in other solar systems, for obtaining a tomographic view of space weather, ultra-high energy cosmic rays and for many other astronomical areas of interest. Because of the low observing frequency the aperture size of the instrument must be in the order of 100 km. This requires a distributed space mission which is proposed to be implemented using formation flying of small satellites. The individual satellites are broken down in five major subsystems: the spacecraft bus, the antenna design, the frontend, backend and data transport. One of the largest challenges is the inter-satellite communication. In this paper the concept and design considerations of OLFAR are presented.

1. Introduction

In 1932 at Bell Telephone Laboratories Karl Jansky built an antenna, designed to receive terrestrial radio waves at a frequency of 20.5 MHz. After recording signals from all directions, Jansky categorized them into three types of static: nearby thunderstorms, distant thunderstorms, and a faint steady hiss of unknown origin. This was the discovery of extra-terrestrial radio signals and in fact the start of radio astronomy science. It took some time before these results were taken serious and radio astronomy started to build new instruments. After

World-War-2 new instruments were built, but at higher frequencies. So, although radio astronomy started at low frequencies, the focus was on higher frequencies.

Research at low frequencies is one of the major topics at this moment in radio astronomy and several Earth-based radio telescopes are constructed at this moment (e.g. the LOFAR project in the Netherlands [3,4], covering the 30- 240 MHz range). It is considered as one of the last unexplored frequency ranges [11]. Low-frequency radio astronomy has focused his operation mainly on the frequency regime above ~50 MHz. Below this frequency, Earth-based observations are limited due to:

- Severe ionospheric distortions
- Complete reflection of radio waves below 10-30 MHz
- Solar eruptions
- Radio frequency interference (RFI) of man-made signals.

There are however, a number of interesting scientific processes that naturally take place at these low frequencies, but which are hampered by the limitations mentioned above.

The band is scientifically interesting for exploring the early cosmos at high hydrogen redshifts, the so-called dark-ages and the epoch of reionization. This frequency range is also well-suited for discovery of planetary and solar bursts in other solar systems, for obtaining a tomographic view of space weather, ultra-high energy cosmic rays and for many other astronomical areas of interest [7].

Because of the ionospheric scintillation below 30 MHz and the opaqueness of the ionosphere below 15 MHz, Earth-bound radio astronomy observa-

tions in those bands would be severely limited in sensitivity and spatial resolution, or would be entirely impossible. A radio telescope in space would not be hampered by the Earth's ionosphere, but up to now such a telescope was technologically and financially not feasible. With today's technological advancements in signal processing and small satellite systems we can design a distributed low frequency radio telescopes in space which could be launched within 10 years time [2][5].

In order to achieve sufficient spatial resolution, a low frequency telescope in space needs to have an aperture diameter of over 10-100 km. Clearly, only a distributed aperture synthesis telescope-array would be a practical solution. In addition, there are great reliability and scalability advantages by distributing the control and signal processing over the entire telescope array.

In OLFAR (Orbiting Low Frequency Antenna for Radio Astronomy), we make use of distributed sensor systems in space to explore the new frequency band for radio astronomy. Such an array would have identical elements, and, ideally, no central processing system. Advantages of such an array would be that it would be highly scalable and, due to the distributed nature, such a system would be virtually insensitive to failure of a fraction of its components. Initially, such a system may be demonstrated and tested in Earth orbits. In later stages, swarms of satellite arrays could be sent to outer destinations in space.

Individual satellites consist of a spacecraft bus and the radio astronomy payload. The payload comprises a deployable antenna for the frequency band between 1 and 30 MHz. The sky signals will be amplified using an integrated ultra-low power direct sampling receiver and digitizer. The signal bandwidth available for distributed processing is relatively low: only a fraction of the bandwidth. Using digital filtering, any subband within the LNA passband can be selected. The data will be distributed over the available nodes in space. On-board signal processing will filter the data, invoke (if necessary) RFI mitigation algorithms and finally, cross-correlate or beam-form data from all satellite nodes [1][8]. If more satellites are available, they will automatically join the array. The final correlated or beam formed data will be sent to Earth. The reception of this data can be done using the

LOFAR radio telescope [4] (by use of the Transient Buffer Board capacity) or using a dedicated system.

Having described the basic ideas of OLFAR, we will focus on the various aspects in the remainder of this paper. In section 2 the limitations of Earth-based observations will be discussed which motivates a space mission for low-frequency radio astronomy. In section 3 a brief overview of the science will be given. This results in a list of specifications and research and design challenges for OLFAR, presented in section 4. A breakdown of the proposed system is presented in sections 5 and 6. Finally, conclusions are drawn and an outlook to further research is given.

2. Why a space mission?

To study the physical processes in the Universe, observations are done at various wavelengths, from Gamma rays to optical and radio frequencies. Only certain parts are not blocked by the atmosphere of the Earth and can be observed by Earth-based observatories. Blocked frequency bands must be observed using space-based instruments. Low-frequency radio astronomy below 30 MHz is recently taken into consideration. Because of the long wavelengths very large scale instruments are required to obtain sufficient angular resolution. Recent technological developments for transporting the huge amount of information makes it possible nowadays to build such instruments [3, 4].

New Earth-based low-frequency instruments are focusing their operation mainly on the frequency regime above ~50 MHz. Below this frequency several problems will occur.

The first problem for radio waves below 50 MHz is the Earth's ionosphere. The ionosphere plasma will scatter the radio waves and below the so-called plasma frequency, propagation of the radio waves is not possible at all. This happens between 5 and 10 MHz (depending on day and night, and on solar activity). Below these frequencies no observations are possible with Earth-based observatories.

But even for higher frequencies the ionosphere causes significant angular displacements, broadening and intensity fluctuations. This can be compared with viewing the sun from the bottom of a swimming pool. The sun can be seen, but the image is blurred by the surface variations of the water.

These distortions are also a challenge for the new low-frequency Earth-based observatories and ionospheric calibration of the instruments is one of the main topics.

Another reason for a space mission is man-made and naturally occurring Radio Frequency Interference (RFI) There are several potential threats concerning the RFI environment of the Earth [9]:

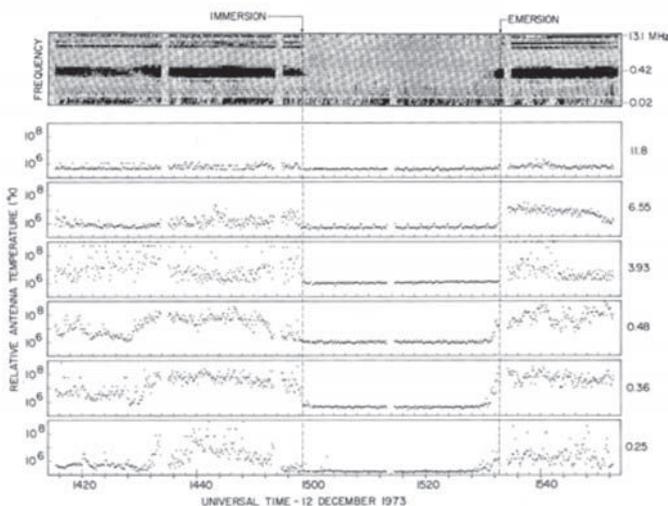
- Earth-bound transmitters, mainly commercial HF transmitters
- Auroral kilometric radiation (AKR), mainly in the 0.15-0.3 MHz band
- Spherics from lightning, burst-like

Depending on the RFI levels, more bits must be used in the A/D converters. This will be a major burden on the computational power needed for the instrument. Similarly, RFI levels will also influence the required data transport bandwidth between the antennas.

A space mission will lower the RFI levels and will allow less bits in the A/D convertors. Clearly, in Moon-orbit (at the backside of the Moon), at the Earth-Moon L2 point, or at the Sun-Earth L4/5 points, these effects will not be present, or will be reduced substantially. Calculations on the RFI levels can be done easily using Free Space Path Loss equations.

Two space missions whose primary purpose was low-frequency radio astronomy have been laun-

Figure 1: Observations of the RAE-2 satellite orbiting the Moon. The shielding of the Earth-based RFI by the Moon can be seen clearly.



ched so far: the Radio Astronomy Explorers (RAE) 1 and 2 (1968, 1973)[10]. RAE-1 orbited the Earth and it detected strong man-made RFI and interference from AKR and from solar winds interacting with the Earth's magnetic field. RAE-2 was therefore sent into a Moon orbit. As can be seen in Figure 1, there is still a lot of RFI present in the data if the Moon is not shielding the RFI from Earth. On the backside of the Moon the RFI levels are very low. A Moon orbit for OLFAR is therefore considered.

We can conclude that low-frequency observations below 30-50 MHz must be done using space-based instruments. In the next section a short overview of interesting low-frequency radio science will be given.

3. Low-frequency science

With OLFAR a new unexplored frequency band will be observed, most likely leading to new discoveries. In [6], Jenster and Falcke made an extensive science case for a low-frequency observatory to be built at the back side of the Moon. This location is almost perfect for a low-frequency observatory: (almost) no man-made RFI, very accurate knowledge of the position of the antennas, and no problems with the Earth's ionosphere. However, Moon-based missions are very expensive. Also making a 100 kilometer distributed array will be a major challenge on the surface of the Moon.

This science case is the same as for OLFAR. The main science drivers are [6]:

- *Cosmology.* What happened in the early universe between the moment of the Cosmic Microwave Background Radiation (CMB) at around 380.000 years after the Big Bang and the Epoch of Reionization (about 400 million years after the Big Bang), the so-called Dark Ages.
- *Extra galactic Surveys and Galactic Surveys.*
- *Transients,* like solar/planetary bursts, X-ray binaries, pulsars, exoplanets.
- *Ultrahigh energy particles.*
- *Tomographic views of space weather.*

And of course "serendipity" since a complete new frequency window will be opened for the first time.

4. Specifications

The main design considerations for an astronomical low-frequency array in space relate to the physical characteristics of the interplanetary and

interstellar medium. The configuration of the satellite constellation and the achievable communication and processing bandwidths in relation to the imaging capabilities are also crucial design considerations. This leads to the main initial specifications of an OLFAR array as listed in Table 1.

To realize such an astronomical instrument in space, several major technical challenges have to be met in the course to final operation of this instrument. The following research and design challenges are addressed.

- *Mechanics and systems engineering.* This includes the mechanical design and implementation of the complete satellite, integration, testing, and preparation of launch ready flight units.
- *Absolute and relative navigation and attitude.* Design of the algorithms and software for determining the relative position and velocity, and attitude and attitude rate of the satellites within the cluster, and also the absolute position and velocity, and attitude and attitude rate of the cluster.
- *Inter-satellite link.* The satellites need to transfer data, spread processor load, exchange house-keeping data and determine their relative distance. For synchronized transmission and

reception, and for correlation, the satellites need to synchronize clocks and reference oscillators.

- *Active antenna system for low frequency radio astronomy.* Design (mechanics and electronics) of the active antenna, including the LNA.
- *Sensors for relative attitude determination.* Development of MEMS sensors to determine the relative attitude and attitude rate of the satellite.
- *Star trackers for absolute attitude determination.* Miniaturizing star trackers with minimal impact on the mass, volume and power budget will be considered.
- *Constellation maintenance.* For the array of satellites it is important to measure, predict and correct for gradually drift of relative positions of satellites. A minimal thrust scenario ensuring a long life-time of the micro-propulsion system needs to be developed.
- *Correlation software and hardware.* Development of algorithms, software and hardware for both the receiving beam for radio astronomy and the transmit beam for the downlink.
- *Protocols.* The OLFAR systems will be open standard and it will be possible for satellites designed by other teams to join the radio telescope network (a real autonomous sensor system).

Table 1. OLFAR preliminary specifications

Frequency range	1-30 MHz
Antennas	Dipole or tripole
Number of Antennas/satellites	50
Maximum baseline	Between 60 and 100 km
Configuration	Formation flying
Spectral resolution	1 kHz
Processing bandwidth	100 kHz
Spatial resolution at 1 MHz	0.35 degrees
Snapshot integration time	1 s
Sensitivity	Confusion limited
Instantaneous bandwidth	To be determined
Deployment location	Moon orbit, Earth-Moon L2 or Sun-Earth L4/5

5. Destination

Based on the specifications, the science objectives, as well as the constraints imposed by the engineering feasibility of various solutions, there are several options for locating the array:

- formation flying in-orbit around the Earth
- in-orbit around the moon,
- Earth-Moon L2
- Sun-Earth L4 and L5, and Earth leading and tailing constellations.

One of parameters for determining the possible destinations is the Earth-bound RFI, especially at long-wave frequencies. A Moon-orbit distributed array would be preferable, in which the Moon-screened elements of the array observe the universe and therefore will not be hampered by Earth-bound RFI as can be seen in Figure 1. The rest of the array could be used for both data processing and for the data link to Earth.

The level of the Earth-bound RFI will determine the number of bits in the Analog-to-Digital converters in the satellites. The number of bits will be of large

impact in the data transfer between the satellites. In case of (almost) no RFI, only one bit sampling is enough for the astronomical signals. Therefore far locations, like L4 and L5 but also other Earth leading or trailing locations will be considered. The drawback of far locations is of course the bandwidth limitation of the downlink.

Another parameter is the stability of the orbit of the destination. One of the requirements is the maximum constellation diameter. This is set to 100 kilometer. That means that all the satellites must be within this range. If a destination is unstable, this condition can not be guaranteed without the need for (expensive) thrusters.

6. System level

OLFAR is aimed to be an autonomous distributed sensor system in space. Such an array would ideally be constituted by identical elements without a central processing system. Such an array would be highly scalable and, due to its distributed nature, it would be virtually insensitive to failure of a fraction of its elements.

Individual absolute satellite positions as well as relative positions between the satellites, attitude, time, and status information, are important information and special positioning and synchronization techniques are required. The satellites are considered to be all identical: no central processing or processing units are available. The need of a mother spacecraft will however be considered in the project. Preliminary design studies suggest that the required functionalities may well be implemented into small satellites. A central satellite might be needed, however, if the communication and processing at the individual satellites can not be fit into the small satellites which constitute the elements of the array. In that case it is possible to send the raw data to a central mother spacecraft for correlation and data downlink.

The individual array elements (i.e. satellites) may be broken down in two parts: the spacecraft bus and the payload. The payload comprises the antenna design, the frontend, backend and data transport. The data transport includes both intrasatellite and inter-satellite transport; it also includes the data transport to Earth.

6.1 Spacecraft Bus

Each element of the system will be an individual satellite. This requires a lot of spacecraft to fill the large aperture. We consider 50 elements as a target scenario. Small satellites are considered as carrier of the individual elements of the instrument.

The spacecraft bus will house the astronomical instrument. The nature of the mission sets some special requirements to the spacecraft:

- The absolute spacecraft position is needed to a high accuracy.
- The relative position between satellites is very important. Decimeter accuracies are needed, even for the longer baselines in space.
- During the observations the attitude of the antennas must be stable.
- Exact timing and synchronization is required to be able to use the system as an interferometer.
- As small satellite systems are considered for the telescope array, and giving the amount of processing that is required, low power systems are clearly needed.

6.2 Antenna concept

The proposed frequency band of the antenna array is 1 to 30 MHz. The power transmitted to the receiver will depend on the antenna length. In the design a deployable wire antenna will be considered. The efficiency drops as the antenna wire is shortened.

The advantage of using tripoles for 3-D imaging is that it does not suffer from gain loss in off-axis antenna directions. Its disadvantage is that tripoles consume three backend input channels per antenna unit. As a result an array of dipoles will have more antenna units and therefore offer better aperture coverage than an array of tripoles for the same dimensions of the backend.

6.3 Frontend

The low noise amplifier is situated directly behind the antenna to limit signal loss and ensure a low contribution of the analogue electronics to the overall system noise power. Since the sky noise temperature is orders of magnitudes larger than the receiver noise, no classical power matching is needed and we can tolerate a serious impedance mismatch and still have the sky noise contribution to the overall system temperature dominate over the receiver noise contribution. Before the received

and amplified signal can be sent to the backend, the signal needs to be converted to an appropriate frequency and digitized. The aim is to develop ultra-low power receiver electronics for amplification of the sky signals and for digitization. The goal is to develop a LNA chip for the frequency range from 1 to 30 MHz. This chip includes an integrated ADC and signal processing hardware. The signal bandwidth available for distributed processing is relatively low: only a fraction of the bandwidth. By digital filtering, any subband within the LNA passband can be selected. Given the fact that the observational frequency is low, direct sampling is applied so there is no need for analog mixing schemes.

6.4 Backend

The data of the individual satellites will be distributed over the available satellites (nodes) in the array. The distributed data processing consists of subband filtering, beamforming, RFI mitigation techniques and correlation. After the processing the correlated data will be transferred to Earth for calibration and imaging. Various signal processing techniques are used, depending also on the mission concept. In case of a Moon orbit mission, part of the array will be screened by the Moon and therefore not hampered by the Earth-bound RFI. The shielded part of the array will be used for reception of the astronomical signals. The rest of the array is used for data processing and the data transport to Earth. Since array nodes will dynamically join and leave the receiving and transmitting subarrays, special configuration and calibration techniques must be considered and studied.

6.5 Data transport

The data transport consists of three elements:

- Intra-satellite wireless data transport (e.g. sensors, positioning data). The function of the intra-satellite data transport subsystem is to transport the signals from the various sensors (e.g. antennas, position, time) to the backend of the satellite. Part of the communication will be done wirelessly.
- Inter-satellite data transport (control, subband data, correlated data). The satellites need to transmit their captured data, position, time, and some other meta information needed for the distributed signal processing (beamforming and correlation) to all the satellites in the array. The data processing is done on all the raw data of all

the satellites. The resulting, correlated and integrated, data stream will have a much lower data rate than the raw data.

- Data communication between the array and Earth (diversity techniques for large array-Earth distances). As the satellites ultimately will be at large distances to the earth and may have large inter-satellite distances, the communication schemes should also allow for communication diversity (clustered transmit and receive schemes).

In addition, there are considerable reliability and scalability advantages by distributing the control and signal processing over the entire telescope array.

One of the main challenges of the OLFAR system design is the inter-satellite link. In the next section a closer look into the inter-satellite link is given.

7. Inter-satellite link

The number of satellites is an important parameter for the design of the inter-satellite communication hardware. Because of the distributed data processing, all the data of all satellites must be sent to all other satellites in a decentralized architecture. Each satellite will choose the relevant channel and will correlate the data.

A baseline is defined as the relative position vector between any two antennas in the array. It is expected that the maximum baseline length for OLFAR will be 100 km. This is either the diameter of a circular or spherical arrangement, or the maximum separation in another shape of a surface-based array. For the inter-satellite communication this maximum number of 100 kilometer will be taken as requirement.

With:

- N_{sat} = number of satellites
- B = observing bandwidth
- f_s = sampling frequency
- N_{bits} = used number of bits
- N_{pol} = number of polarizations

the data rates between the satellites can be calculated as follows:

$$R_{\text{sat}} = 2BN_{\text{bits}}N_{\text{pol}} = f_s N_{\text{bits}} N_{\text{pol}} \quad (1)$$

$$R_{\text{tot}} = N_{\text{sat}} R_{\text{sat}}$$

For the current design of OLFAR the values are $N_{\text{sat}} = 50$, $B = 1$ MHz, $f_s = 2$ MHz, $N_{\text{bits}} = 1$, $N_{\text{pol}} = 2$.

This results in a data rate of 4 Mbps for each satellite, adding up to a total data rate of 200 Mbps of the total array. Note that these are the numbers for 1 bit sampling! In case of 8 bit sampling, the numbers will be 32 Mbps for each satellite and 1.6 Gbps for the array.

Each satellite will send its data to all the other satellites. Several techniques can be used to assure that the appropriate data can be selected by the individual nodes. The possible dimensions for multiple access are time, frequency, code and space. One of most straightforward implementations is frequency division multiplexing (FDM). Each satellite will transmit its data using (eg) PSK-modulation in a narrow bandwidth channel. The channels are separated by large guard bands to prevent interference between the channels. If each channel is transmitted simultaneously, the overall data rate will be the sum of all the channels.

A more efficient modulation is required for high data transmission. One of the promising techniques is OFDM (Orthogonal Frequency Division Multiplexing). OFDM had been adopted as standard for DVB, DAB and WLAN. With OFDM, the separation between each channel is equal to the bandwidth of each channel, which is the minimum distance by which the channels can be separated.

8. Conclusions and outlook

In this paper we propose a novel and innovative concept for a radio astronomy at very low frequencies. As the Earth's atmosphere excludes observations at these frequencies, we present OLFAR, the orbiting low frequency antennas for radio astronomy in space. To realize a large aperture, a decentralized space architecture is to be developed, which consists of multiple satellites flying in formation. Each satellite receives the astronomical signals and shares these data with all the other satellites. Data processing is done in space and the processed data will be sent to Earth for further off-line processing. The key communication challenge is the inter-satellite communication.

This concept holds a variety of opportunities and challenges which require more detailed research. This includes simulations of the satellite array at various locations in space, virtual distributed system and satellite architecture design, design of radio architectures for the communication in distri-

buted arrays and distributed autonomous signal processing.

With OLFAR we propose an autonomous sensor system in space to explore this new frequency band for radio astronomy. We expect this route will lead to new science both in astronomy, space science and engineering.

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Double Solenoid ELF Magnetic Field Exposure System for In-Vitro Studies

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Abstract

Concerning in-vitro biological studies, it is necessary that a well-characterized exposure system is used particularly to validate and replicate key findings. Therefore, we improved and characterized an ELF magnetic field exposure system with high dynamic exposure range (μT - mT) and reduced stray magnetic fields for a 50/60 Hz sinusoidal signal. The basic design is based on a double solenoid setup. The outer solenoid is used for the reduction of the stray B-flux densities. The system itself is modular to adapt to different biological experiments. To be able to apply a high dynamic exposure range a controlled air cooling system is added. The exposure system is using a control algorithm and associated Graphical User Interface. Temperature is measured and controlled inside the exposure area. The exposure characteristics along with temperature variation are monitored and recorded during the experiments. In conclusion, the ELF exposure system is well suited to conduct a wide range of real and sham ELF magnetic field cell-exposure studies.

Introduction

Concern on possible health hazards due to exposure to ELF-MFs has led to the development of various exposure setups to support biological investigations, both for in-vitro and in-vivo studies, to examine possible effects and mechanisms of the ELF-MFs on biological systems ([1]-[8]). However, the causality of ELF-MF exposure effects is still an open issue. Replication of key findings by different laboratories is also very difficult due to incomplete characterization of the used exposure setups. Hence, the design and characterization of the exposure setup is, to our opinion, paramount within any research program involved in this field.

The most widely used exposure systems for magnetic field generation are exposure systems with simple geometrical shapes; systems with circular, square and rectangular coils of two or more windings with various spacing between the windings. For an overview of the generally used exposure systems we may refer to Gottardi et al. [1]. In recent years, more advanced systems have been designed allowing monitoring and recording of the exposure characteristics throughout the whole duration of the experiments [8].

The objective of this research was the development and characterization of an ELF-MF exposure setup with a high dynamic range (μT - mT) of uniform B-flux density exposure at 50 or 60 Hz and low stray magnetic fields, to support in-vitro biological experiments. The system was designed to fit inside a commercial CO_2 cell culture incubator. A controlled air cooling solution was developed to regulate and monitor temperature within the exposure area. In our research framework an important issue is the reproducibility of the biological experimental results. To support this a Graphical User Interface (GUI) for monitoring and recording the temperature and supplied electrical parameters during the experiments has been developed.

System design

A. Exposure Coil Design

The exposure system (see Fig. 5) is based on an existing configuration of a double solenoid with double windings that fits inside a commercial cell culture incubator. The outer solenoid consists of two concentric coils with an inverse direction with respect to the electric current supplied to the main solenoid. This approach is known as the active magnetic shielding method used to reduce stray

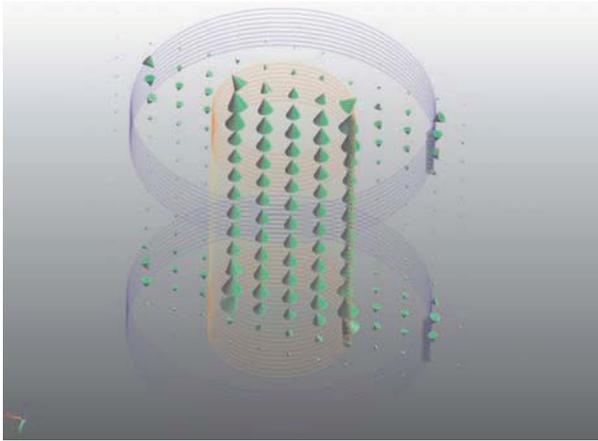


Figure 1.: Simulated values of our basic ELF exposure design and vector field view of B-flux density depicted by the green arrows. The cone end-points pertain to the orientation of the B-flux vector. The cone size represents the B-flux magnitude.

magnetic fields [7]. The compensation coils are symmetrically oriented with respect to the center of the system, consisting of equal number of windings. As stated in [7], the concentric compensation configuration has the advantage of reducing the fields in all directions. This statement has been observed during our analysis also. However, the compensation coils do deteriorate the field intensity in the exposure volume. To compensate for this amplitude reduction, double windings are placed at the edges of the inner solenoid. To clarify the previous, a vector view of the resulting B-flux density in a vertical cut is shown in Figure 1.

For design and analysis, a simulation model designed in SEMCAD X (Version 14.2.1, Schmid & Partner Engineering AG, Zürich, Switzerland) of the exposure coil has been used.

B. Cooling System Design

According to biological conditions inside the exposure environment the temperature should remain with a maximum fluctuation interval. The allowable fluctuation depends on the type of biological experiments. The maximum achievable B-flux density is limited by the induced temperature-rise above its user defined limit.

The basic ELF exposure configuration is capable to support a natural airflow for keeping the temperature stable within its limits. However, our preliminary experiments revealed that this airflow is not sufficiently enough to support the whole dynamic range up to $1 \text{ mT}_{\text{rms}}$. Hence an additional temperature-controlled cooling system that will not influ-

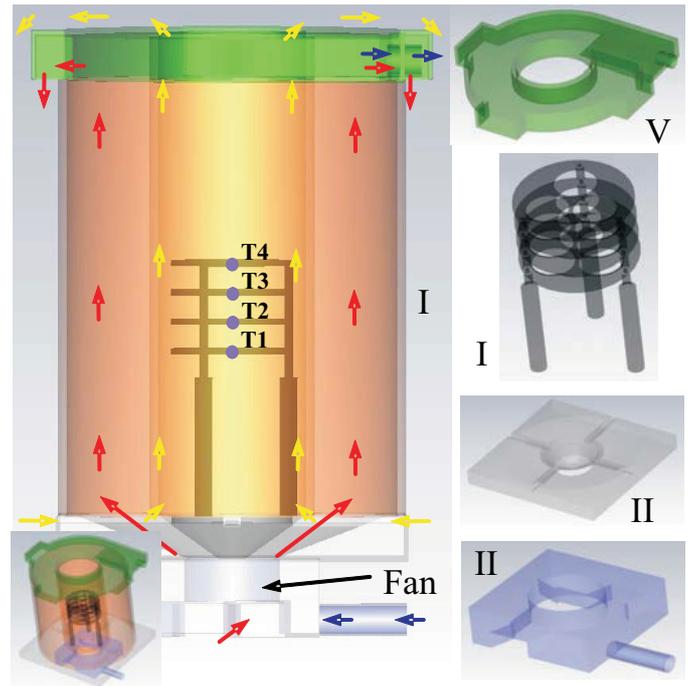


Figure 2.: Design of our temperature controlled air-cooling system (The red arrows depict the forced airflow where the yellow arrows depict the natural airflow)

ence the actual experiments is needed. We decided to design this cooling system based on forced airflow [8]. Our design is presented in Figure 2 where the three mechanical parts (II, III, V) necessary to appropriately distribute the air through the system are separately indicated. A 48V DC fan (San Ace 120L) is used to minimize the presence of the parasitic B-flux density introduced by the coil inside the fan motor. The maximum airflow is 180 CFM.

The cooling system is controlled by adapting the fan rotations using Pulse Width Modulation (PWM) and basic EMC-measures are taken into account. The actual temperatures present at several locations in the exposure area are measured using a LabJack U6 Pro Data Acquisition (DAQ) system. The temperature sensors we use are Type-K thermocouples with an accuracy of 0.12°C . The thermocouples are placed on the Petri Dish Carrier (PDC, see Fig. 2 part IV). This PDC consists of four plates which could be taken out of the system. Each plate is able to carry one Petri Dish of 88 mm diameter or three Petri Dishes of 54 mm diameter and each plate has its own temperature sensor that is mounted in the middle of the plate indicated with the dots marked T1 to T4 (see Fig. 2 part I). T3 is used for controlling the fan where the other sensors are used for monitoring and recording the tempe-

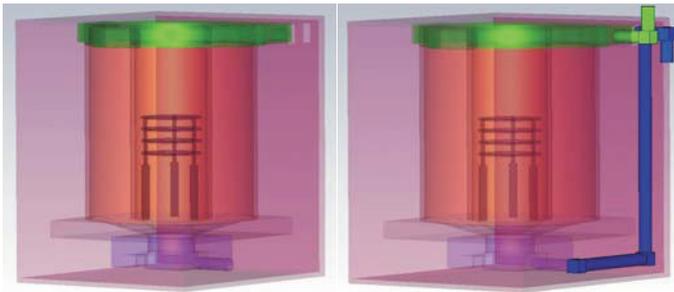


Figure 3.: Exposure system in an incubator with the intra-incubator setup (left) and inter-incubator setup (right) where the green pipe is the outlet and blue the inlet.

perature difference within the exposure area. The fan is mounted on the "inlet adapter" (II) where through the "fan adapter" (III) the air is distributed with equally spaced velocity to enable a circulating airflow- like a vortex - through the system. In Figure 2 the forced airflow is depicted with the red arrows. It is noted that forced air only moves within the inner and outer cylinder where the heated copper wires are. At the top the heated air is distributed through the "outlet adapter" (Fig. 2, part V) thereby preventing the heated air to flow into the inner cylinder area. This approach avoids interaction with biological materials. To ensure that the air composition (i.e. the possibility to add CO₂) in the inner cylinder area is the same as in the rest of the incubator we created four channels (Fig. 2 part III) to support the natural airflow. This natural airflow is depicted with the yellow arrows.

The cooling capacity of our forced air cooling concept when placed in the incubator is limited since in general an incubator is not equipped with air-conditioning but with heating elements only. To be able to adapt this system to different kind of biological experiments and incubators, we created two different cooling setups, the so called "Intra-incubator" and "Inter-incubator" setup (See Fig. 3).

The "**Intra-incubator**" cooling setup is based on a closed air circuit which means that there is no air drawn from outside the incubator to circulate inside. The heated air is distributed by the cooling system to a larger volume away from the exposure area. This results in a delay in the warming up of the complete system until it reaches temperature equilibrium.

The "**Inter-incubator**" cooling setup mainly circulates the air inside the incubator and partially draws air from outside as depicted in Figure 3



Figure 4.: Graphical User Interface. On the left is the control and on the right the temperature readout.

(right picture). Through the blue pipe the much cooler external air ($\Delta T > 12^{\circ}\text{C}$) - with a maximum of 5 CFM - is mixed with the heated air within the system. In this case the amount of air that could be drawn from outside the incubator is limited by the diameter of the access port at the rear wall of the incubator. The access port diameter differs per incubator type. In order to avoid over- or under-pressure it is important to ensure that the same amount of heated air is blown externally via the green pipe and equals the amount of air that is extracted from the outer environment.

C. Graphical User Interface

The GUI shown in Figure 4 is used to set and control the fan speed (PWM) - which influences the airflow - based on the actual temperature measured. The software has an algorithm which could be adjusted to defined temperature thresholds. The GUI visualizes the temperature history in a graph and the values of the air flow (CFM), electric current (A) and associated B-flux density (mT). There is also the possibility to store all these values and to be informed by e-mail when the measurement has finished.

D. Exposure Apparatus

In Figure 5, the total exposure design as described in chapter II A consisting of the attached "fan adapter", the Petri Dish Carrier, a personal system depicting the GUI and the housing of the DAQ and control system is presented. The PDC is carrying two Petri Dishes of 54 mm diameter filled with saline solution.

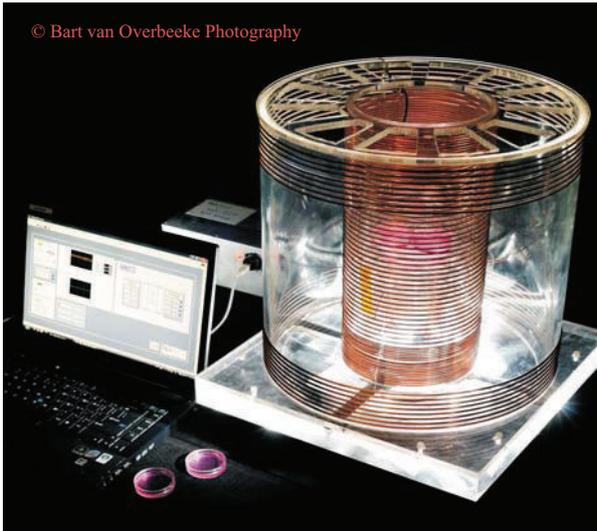


Figure 5. Basic exposure system with attached "fan adapter". The GUI is depicted in the right and the housing of the DAQ and control system is depicted at the right back corner.

System characterization

E. B-Flux Density

At first we simulated the whole coil setup. The numerical model consists of separate coils. The resulting B-flux density, is analyzed by using SEMCAD X. By using Biot-Savart's law the total B-flux is computed as the superposition of the B-flux densities of the separate coils. To investigate the uniformity of the B-flux distribution, we define our reference point at the centre of our exposure system. The B-flux at the center is denoted by B_0 .

The Uniformity of B-flux density of the exposure system is defined as

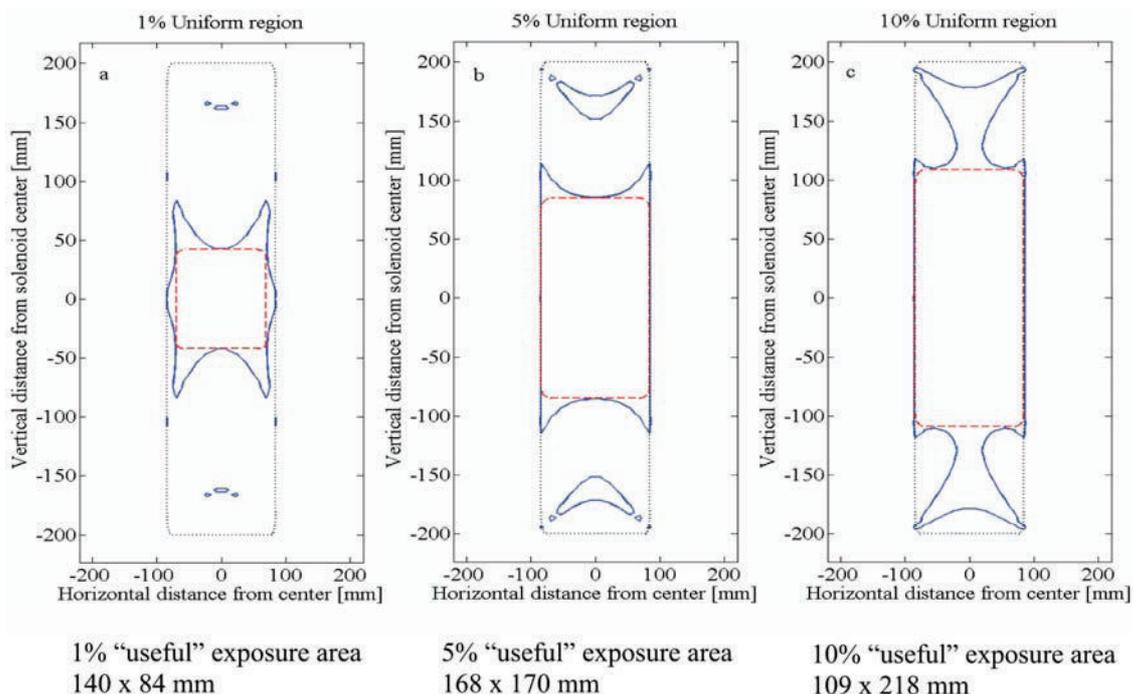
$$U = \frac{|B - B_0|}{|B_0|} 100\% \quad [1].$$

The 1, 5 and 10% uniformity areas in vertical cuts are depicted in Figure 6. The red dashed lines indicate the "useful" exposure area. The term "useful" is introduced to characterize the area that can actually be used for ELF-exposure of the biological samples. The geometrical characteristic of the exposure system and the size of the "useful" exposure areas as computed through simulations are listed in Table I.

The reduction of the stray magnetic fields outside the incubator is deemed necessary to minimize EM coupling with neighboring electronic devices and enable closer proximity of an additional ELF exposure system in the same or a second incubator. Computing the influence of the the compensation coil, we obtain 16 dB and 17 dB reduction of stray B-flux densities, at 640 mm and 520 mm horizontal and vertical distance from the solenoid center, respectively. At approximately 320 mm and 260 mm in both planes the compensation coil doesn't result in the decrease of the stray B-flux density.

To validate the simulation results we conducted several measurements where the B-flux density of the ELF-MF exposure system and the homogeneity

Figure 6.: Uniform areas of 1, 5 and 10% of the exposure areas in vertical cuts (blue line). "Useful" area (red dashed line). Total exposure area (gray dashed line).



COIL SETUP ^a	Inner Solenoid (mm)	Outer Solenoid (mm)	Single Windings (mm)	Double Windings (mm)
Coil radius	92.5	200		
Length of the solenoid	392	392		
Number of windings	68	18		
Pitch of the windings			8	4

a: L = 0.26 mH, R = 0.15 Ω (wire "d" of 3mm)

Table 1.: Essential characteristics of the exposure system .

of the exposure volume have been determined. We used a 3-channel Hall effect Gaussmeter (Model 460, Lake Shore Cryotronics, Inc.) with $\pm 0.1\%$ accuracy of reading, equipped with a 3-axis temperature regulated magnetic field probe (High Sensitivity Probe, MMZ-2502-UH, Lake Shore Cryotronics, Inc.) of 4.6 mm probe diameter and resolution of 0.1 μT . The probe was handled by a positioner constructed of foam for the mapping and alignment of the probe. Foam has been used to avoid the perturbation of the measured B-flux density. The measurement setup was designed to perform measurements every 5 mm. The 1% uniform region as determined through simulation and measurement data is compared in Figure 7. The measurement results deteriorate the "useful" exposure area by approximately 2 mm compared with simulations. This discrepancy can be explained by the uncertainty of the probe position. However, we consider the results to be in excellent agreement.

F. Electric Fields

At ELF frequencies, non-magnetic biological systems do not perturb the magnetic field and time

varying ELF-MFs induce internal electric fields determined by Faraday's law of induction which for a Petri Dish of radius r and B-flux density of frequency f is defined as

$$E_{rms} = \pi r B_{rms} \quad [2].$$

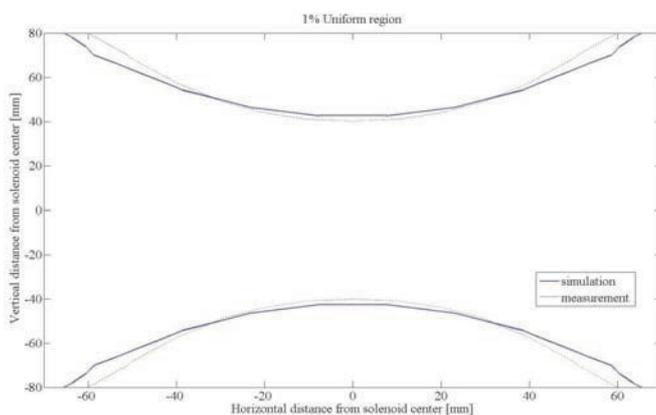
The induced electric field generates a current density in the conductive medium which according to Ohm's law is directly proportional to the electric field strength but depends also on the conductivity of the medium.

The exposure of biological samples in a highly uniform magnetic fields results in highly non-uniform induced electric fields and current densities but low within the medium. For 1 mT_{rms} exposure, the order of magnitude for the electric field is 4 mV/m (SAR values less than 10^{-10} W/Kg). The magnitude and spatial distribution of the induced electric fields are relatively low and highly dependent on the tissue container geometry.

G. Temperature Development

While characterizing this system we studied different quantities in relation to the applied B-field from 5 μT_{rms} up to 4 mT_{rms} as documented in Table II. It clearly shows that there is already a ΔT of 2.5°C for 1 mT_{rms} where 11.32 Watts have to be dissipated. As for the wire (diameter = 3 mm) of the coils it should be capable to easily support the applied current but nevertheless resulted in an increase of temperature. This is mainly caused by the specific solenoid setup. The coils are partially embedded in the PMMA cylinders. This means that only half of the wire is exposed to the environmental air and thus limited to dissipate the heat through natural airflow which, as it turned out to

Figure 7.: Comparison of 1% uniform region



B-Field mT	Current A	Voltage V	Power W	Temperature ^a ΔT °C ^a
~0.005	0.035	0.006	0.0002	-
~0.5	4.45	0.71	3.16	-
~1.0	8.45	1.34	11.32	~2.5
~2.0	16.55	2.61	43.20	~12.0
~4.0	33.34	5.30	176.70	~34.0

a. Environmental temperature $T = 23^{\circ}\text{C}$

Table II.: Relation between applied b-field and temperature.

be, is not sufficient enough for the entire dynamic range (See Table II).

As described earlier we introduced two cooling systems which primarily differ by whether or not external air is used to obtain heat exchange with the outer environment. It is noted that the incubator access port limits the amount of air, in our case 5CFM maximal. Both system setups were tested inside an incubator and the outcome is presented in Figure 8.

What this graph clearly shows is that both systems regulate the temperature variation below the user defined limit of $\pm 0.5^{\circ}\text{C}$ (red dashed lines) within the specified exposure time of 30 minutes (sample rate is 2 s). This limit is variable and depends on the possible biological studies determined by the researcher. In both cases the fan worked with a duty cycle of 100% and thus with a maximum airflow of 180 CFM. The graph also shows that it is not necessary for the "Inter-Incubator" setup to run the fan constantly or with the highest speed. For that we introduced a fan controlled algorithm. This algorithm consists of controlling the speed of the

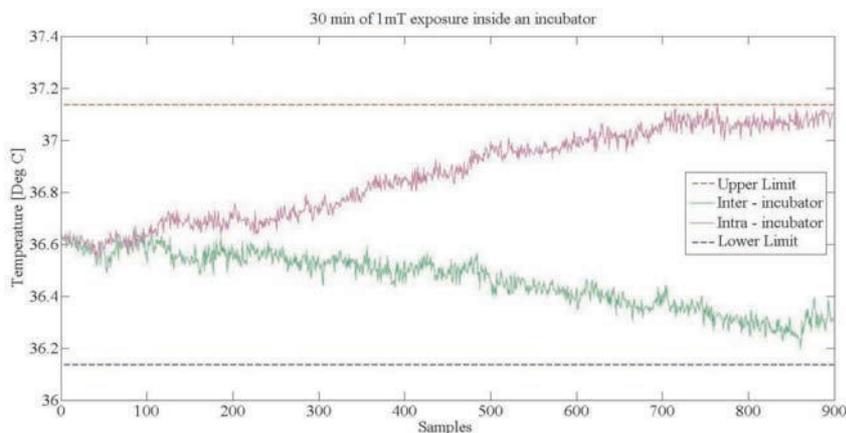
fan by varying the duty cycle based on the actual temperature variation from the reference temperature (ΔT). The higher the ΔT the higher the fan speed will be. Adapting this algorithm to the "Inter-Incubator" setup it resulted in an average duty cycle of approximately 80%.

To complete our research on this topic we monitored the three other temperature sensors placed on the PDC during the earlier described measurements. The maximum temperature difference between the top and bottom carrier plate temperature sensor is approximately 0.15°C .

Discussion

In this paper we designed and determined the performance of a simple however advanced ELF-MF exposure system for in-vitro studies. We concentrated on the size of the exposure apparatus, on the reduction of the stray magnetic fields outside the incubator, and on the temperature regulation for high B-flux densities. To reduce the stray magnetic fields a concentric compensation coil configuration was chosen. The coils are connected in series avoiding amplitude differences in the current and

Figure 8.: Comparison between "Intra-incubator" and "Inter-incubator" temperature measurements.



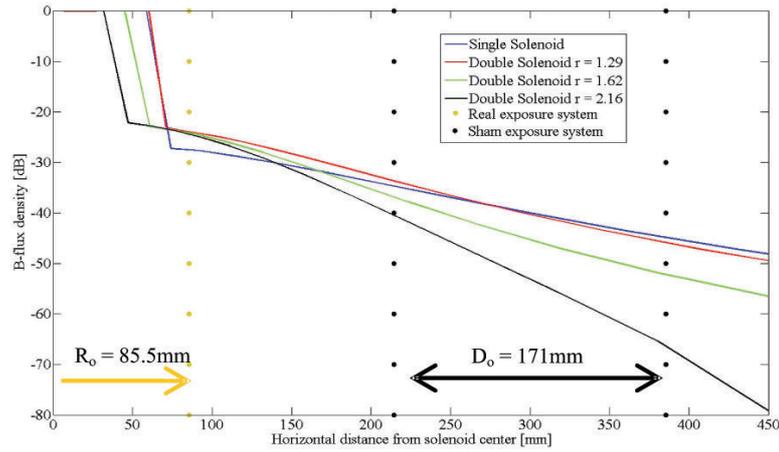


Figure 9.: Comparison of horizontal B-flux distribution of three Double Solenoids with a Single Solenoid. Real (yellow dots) and sham (black dots) exposure systems are 140mm apart.

phase shift between the inner and outer coil configuration. These are known difficulties at individually driven coils as described in literature [2, 8].

According to our design one system fits inside a commercial incubator. To house two systems, for real and a sham exposure, inside the same incubator two issues should be addressed namely; (1) the minimization of the exposure system and (2) the use of bifilar coils. Bifilar coils are double wound so we can ensure that real and sham exposure system [1, 2, 8] have similar heat production. When the windings are driven by currents of opposite direction the net B-flux density is zero for the sham exposure. To enable the proximity of the two systems the limitation of stray magnetic fields in shorter distance is an important feature. Three systems with double solenoids and different ratios of

the outer and inner solenoid radius (r) but with the same volume (radius of outer solenoid and height are kept constant) are compared with a single solenoid system. Figure 9 depicts the horizontal B-flux distribution for four minimized exposure systems correspondingly.

The system with inner and outer radius $R_i = 39.5$ mm and $R_o = 85.5$ mm respectively, maintains the ratio (r) of the original design. Figure 9 depicts also two exposure systems in vertical cuts separated by 140 mm. Increasing the ratio (r) of the outer compensation solenoid radius over the inner solenoid radius, results in higher reduction of the stray magnetic fields. However, this leads to smaller inner solenoid radius thus deteriorating the "useful" exposure volume. Table III summarizes the geometrical and physical characteristics of

Table III.: comparison of different solenoid configurations.

	Single Solenoid (mm)	Double Solenoid $r = 1.29$ (mm)	Double Solenoid $r = 1.62$ (mm)	Double Solenoid $r = 2.16$ (mm)
Inner radius (R_i)	66	66	52.5	39.5
Outer radius (R_o)	-	85.5	85.5	85.5
Overall Volume (V)	$2.32d^3$ ^a	$2.32d^3$	$2.92d^3$	$3.89d^3$
Uniformity region 1% (U_1)	$0.72d^2$	$0.77d^2$	$0.78d^2$	$0.78d^2$
Uniformity region 5% (U_5)	$1.40d^2$	$1.38d^2$	$1.91d^2$	$2.20d^2$
V/V_1	$3.24d$	$3.01d$	$3.73d$	$4.99d$
V/V_5	$1.66d$	$1.69d$	$1.52d$	$1.77d$

a: "d" is inner solenoid diameter ($2R_i$)

the four (4) exposure systems, following the example of Gottardi [1].

Conclusions

According to simulations and experiments we conclude that the outer coils reduce the stray B-flux density significantly in comparison with a single solenoid. This prevents influencing the environment where possibly other experiments are conducted. The outcome of varying the diameter of the inner and outer cylinder and thus the diameter of the coil introduced the possibility to create a smaller design so a real and sham exposure system could fit in one incubator. Depending on the biological experiments a specific tolerance of the homogeneity can be chosen with a trade off for the "useful" area. The exposure dynamic range that can be chosen is somehow limited by the temperature rise but with the introduction of the air cooling solution it is possible to use this design up to 1 mT for the "Intra-Incubator" setup. All values can be monitored and recorded so different experiments can be compared with accurate knowing of the circumstances.

The Petri Dish Carrier supports in many ways the experiments, by its specific design reproducibility for the two Petri Dishes is guaranteed. The temperature sensors are close to the samples so the temperature in that area is accurately determined. The PDC is placed on rubber blocks so heat conduction and vibrations have negligible values. The system is useful for a wide range of biological experiments with the advantage that every important quantity is recorded which makes it a well-characterized system.

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A Composable and Predictable On-Chip Interconnect

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Monolithic Integrated Reflective Transceiver in Indium Phosphide

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Y. Pu

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Computation of stochastic observables in electromagnetic interaction theory - Applications to electromagnetic compatibility

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High-Efficiency Linear RF Power Amplification - A Class-E Based EER Study Case

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Flexible and self-calibrating current-steering digital-to-analog converters: analysis, classification and design

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Flexible Phase-Locked Loops and Millimeter Wave PLL Components for 60-GHz Wireless Networks in CMOS

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Concepts for Smart AD and DA Converters

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Identification of Low Order Models for Large Scale Processes

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Adaptive RF front-ends: providing resilience to changing environments

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Signal Processing for LED Lighting Systems - Illumination Rendering and Sensing

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Characterization of uterine activity by electrohysterography

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Flexible distribution systems through the application of multi back-to-back converters: Concept, implementation and experimental verification

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Robust sigma delta converters and their application in low-power highly-digitized flexible receivers

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Testing reactive systems with dataenumerative methods and constraint solving

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Coding and modulation for power and bandwidth efficient communication

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Electronic devices fabricated at CMOS back-end-compatible temperatures

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Work flows in life science

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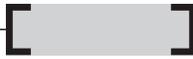
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8 colleges van ieder 4x drie kwartier. Exacte data en tijden volgen zodra het rooster van de TUE 2012/2013 bekend is. 8 x 1 ochtend/middag per week in september en oktober 2012; Eindhoven

Mastercollegeserie - advanced actuator systems

8 colleges van elk 4 x 3 kwartier; Exacte data en tijden volgen zodra het rooster van de TUE 2012/2013 bekend is 8x een ochtend/middag per week in september en oktober 2012; Eindhoven

Mastercollegeserie - hoogspanning I

12 colleges van telkens 2 x 3 kwartier. Exacte data en tijden volgen zodra het rooster van de TUD 2012/2013 bekend is. 12x een ochtend/middag per week van september t/m december 2012; Delft

