

SIMULATION AND INVESTIGATION OF 2D AND 3D PHOTONIC DEVICES

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Abstract

The need for computer aided design and numerical simulations of the PBG-based devices are discussed. The software package, providing an easy way for the investigation of electrodynamic properties of 2D PBG devices/circuits by means of carrying out the series of numerical experiments is presented. The created software package can also deal with high-density integrated optics components that contain optical waveguides, scatterers, resonators and other functional elements. One of the main objectives of this paper is to demonstrate the efficiency of the Method of Auxiliary Sources (MAS), for simulation and study of PBG-based antennas or other (compound) electronic devices. The experimental verifications of the numerical results for elementary devices were conducted for several cases. The large-scale prototypes that were created and tested for these cases are discussed. Topics in this paper are related to up to date problems and connected with state-of-the-art technologies - hopefully, nanotechnologies become more and more widespread and systems like those based on PBG phenomena will become more popular and efficient.

1. INTRODUCTION

Photonic devices attract increasing interest of the international scientific community due to the novel functionalities they offer for the electronic devices in

optical and higher-frequency ranges. This term is referred to as "photonic" band gap, as it was first discovered and used in optical applications (theoretical foundations were first proposed in [1-4]). Though, the electrodynamics theory allows band gaps to be observed for any other parts of the spectrum, rapidly increasing their area of application (This is why some authors refer to "electromagnetic" band gap, while others use "photonic"). Band Gap-based devices in terahertz frequency range promise to solve numerous problems of miniaturization, loss reduction and optimization of functional elements for the new generation of integrate circuits. The variety of microwave devices such as waveguides, filters, mixers splitters and similar tools can be effectively created using photonic crystals as core elements. Such functional elements are crucial counterparts of large complicated integral circuits. Elements like mixers, splitters, frequency filters etc. are widely used in the super-high frequency band. The growth of the operating frequency, however, rather complicates the preparation of such devices using conventional design and fabrication techniques. At the sub-millimeter, terahertz and optical frequencies this special kind of devices (referred to as photonic devices) turn out to be extremely efficient, having improved flexibility and decreased energy losses in comparison with their traditional counterparts. The main part of such device is a dielectric crystal with appropriately arranged defects ("defects" may denote either injected materials, or extracted nodes of the crystal lattice). Due to the nature of photonic crystals there are gaps in their spectrum that cause some frequencies to be filtered out, while others can pass through. In contrast to the ordinary absorbing medium, that transforms the power of electromagnetic wave to heat, the band-gap medium does not dissipate energy. Rather, in this case, the EM field energy is accumulated and can, further, be headed to any desirable direction. The distribution of defects in the crystal defines its behavior with respect to the penetrating wave. Correspondingly, the crystal can split, mix, or filter the incident wave field. For instance, one may make several different "canals" in the crystal, having different resonant properties, which will permit the propagation of waves of certain frequencies, while restricting it for the others.

In general, an experimental investigation of such structures is rather expensive, time consuming and, in some cases, even impossible as the traditional techniques of experimental investigation, design and fabrication fail. Two main reasons are that some of the system properties that can not be changed continuously, "on-the-fly", and

there are also certain technical limitations for defects' positions and sizes. This is the place where the computer aided design and numerical simulations become vitally important and the need for powerful software, capable of comprehensive investigation and analysis of the PBG devices and, based on them, circuits, comes to the forefront.

We have developed the program package for a numerical simulation of the wave propagation in FPC structures. The created software is intended to real-time FPC analysis and development for the device performance optimization. The new technique for prediction of manufacturing uncertainties influence on the working characteristics of the device is introduced. The numerical results for some of the simulated functional elements are discussed and the example of an integral scheme is presented.

2. THEORY AND METHODOLOGY OF THE SOLUTION

Though the computer simulations are easier for 2D case, there appear some technical difficulties with for the experimental measurements. As it is impossible to compactly and accurately simulate the 2D problem in 3D space, we use the well known fact, that the structure of interest can be placed between the two perfectly conducting plates (PCP). The distance between plates depends on the wavelength and it would not be less then quarter of it. Such "sandwich"-like structure with dielectric material between two perfectly conducted plates makes the experimental evaluation of the problem with otherwise infinite in z-direction geometry pretty straightforward.

A dielectric rectangular body with periodically distributed dielectric or metallic rods inside has been taken as a photonic crystal (Figure 1). However, not only the periods in x and y coordinate axes may differ, but also some defects may be introduced by replacing certain rods or changing their parameters. The excitation stimulated by the linear current flowing along the cylindrical wire can be applied at an arbitrary point of the crystal. In reality this one corresponds to the excitation via discontinuous wire at the corresponding point in the "sandwich". The corresponding EM problem is solved by using the Method of Auxiliary Sources (MAS) [5]. The entire 2D dielectric space is split into several domains: outer space, inner crystal space outside the rods and space inside the rods (See Fig. 1.).

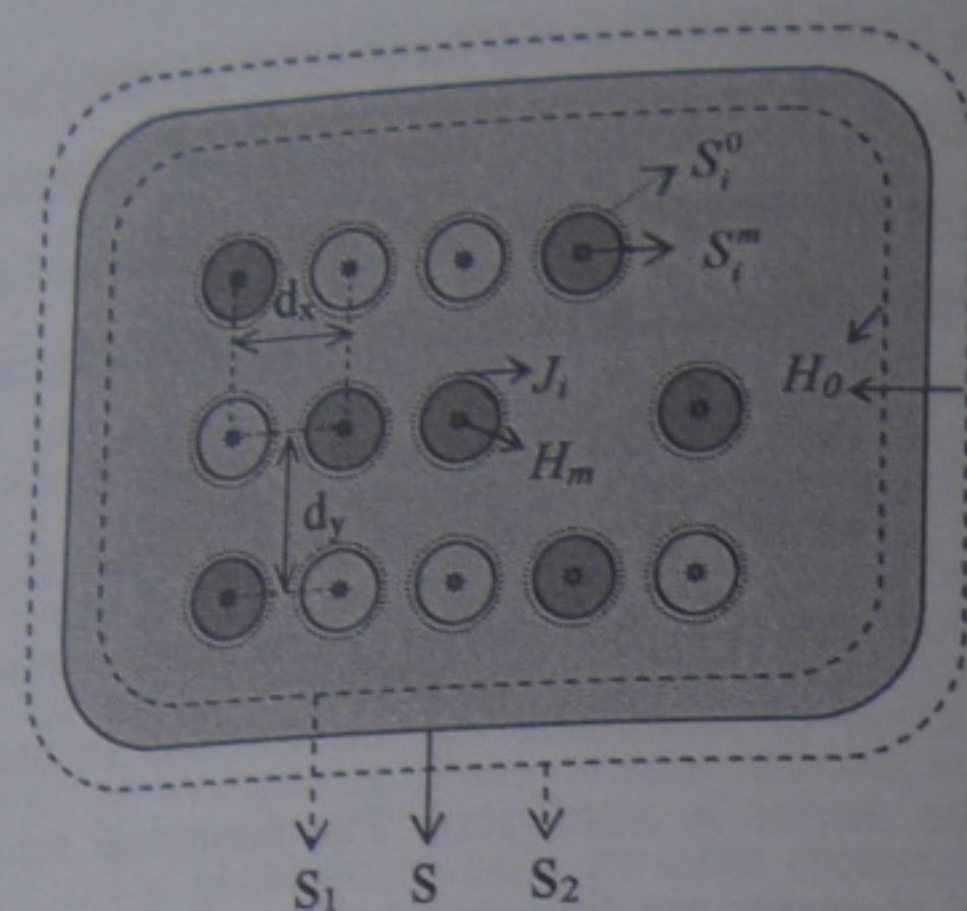


Figure 1. The MAS simulation scheme

The sums of the zero order, first kind Hankel's functions with unknown coefficients are used for the auxiliary sources located along the surfaces S_1 and S_2 and are responsible for the representation of scattered fields in the inner crystal and outer space areas correspondingly. While, the high-order multiple functions are placed inside the rods, that simulate their scattered field inside the crystal. Such representation is valid, though, only if the shape of the rods is circular (or satisfies the conditions of the Rayleigh's hypothesis) and the scattered field singularities are within the circle bounding the rod [5-7]. To find the fields inside the rods sum of the Bessel functions are used, located uniformly around the rods.

Thus, the fields inside the rods are then given by the sum of fields of corresponding circumscribed sources:

$$U_{inside} = \sum_{n=1}^{N_1} \sum_{m=-M}^M A_{nm} J_m(k_2 \rho_n) e^{im\varphi_n} \quad (1)$$

The total field inside the crystal medium (with electrodynamic parameters ϵ_1 and μ_1) is given by the superposition of the field scattered by the cylindrical rods and the fields due to the outer layer of auxiliary sources (S_1):

$$U_{outside} = \sum_{n=1}^{N_1} \sum_{m=-M}^M B_{nm} H_m^{(1)}(k_1 \rho_n) e^{im\varphi_n} + \sum_{\nu=1}^{N_2} C_{\nu} H_0^{(1)}(k_1 r_{\nu}) \quad (2)$$

Finally, the field outside the crystal is determined by the auxiliary sources uniformly distributed on the inner surface (S_2):

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$$V_{rods} = \sum_{\nu=1}^{N_2} D_{\nu} H_0^{(1)}(kr_{\nu}) \quad (3)$$

Here $k_2 = \frac{2\pi}{\lambda\sqrt{\epsilon_2\mu_2}}$ and $k_1 = \frac{2\pi}{\lambda\sqrt{\epsilon_1\mu_1}}$ are wave numbers for the crystal and rods

respectively. If the rods are made of perfect electric conductor, there is no field inside them and the corresponding sources are not accounted.

Unknown coefficients A_{nm} , B_{nm} , C_{ν} and D_{ν} are to be determined by satisfaction of the corresponding boundary conditions on the metallic rods' and dielectric crystal's surfaces. The total number of collocation points depends on that on the dielectric surface, each of the rods and the number of the rods.

The boundary conditions are then used to construct and solve the system of linear equations in complex space (amplitude and phase) relatively to all the unknown amplitudes. Such system is always solvable, ensured that the number of unknown amplitudes equals the number of collocation points and the collocation points themselves do not overlap.

The next issue is to estimate and maintain the accuracy of the problem solution. The straightforward approach is to monitor and control the satisfaction of the boundary conditions. Using the MAS approach it can be easily done, as soon as the functions representing the fields do not have singularities on the region boundaries (This property of the MAS is one of its main privileges). As soon as the field values are rigorously bound in all the collocation points, the upper-limit for the residual evaluation is obtained by monitoring the inaccuracy of the boundary condition satisfaction in the region between the collocation points (half-way between two adjacent points). The data between each pair of points is then integrated over the bounding surface, giving the essential information of the solutions' accuracy.

The results, obtained by computer simulations based these expansions, demonstrate the ability of such structures to serve as a core elements in complicated optical and SHF devices, as well as the abilities of the software to simulate and analyze different structural configurations in order to avoid expensive and time-consuming experimental investigations.

The software has been created for comprehensive investigation of EM processes in 2D periodic lattices. The software grants comprehensive user friendly interface for

creation of the required crystal geometries by means of providing effective tools controlling the types, shapes and placements of node elements, EM field sources and dielectric body boundaries. The user may explicitly specify the parameters controlling the simulation or visualization process: for example, the number of steps in case of parametric calculations involving step-by-step changes of selected quantities; rate of the allowed uncertainty during the evaluation of device's stability during manufacturing; visual color maps for field value outputs; etc...

Using this software, several numerical results for operation of various functional elements and devices in optical range were obtained and verified on the large-scale prototypes of these devices with the help of *HP 8410A Network Analyzer*. Note, however, that though the inaccuracy in numerical simulations was maintained to be within 5%-10%, we did not require high accuracy rates in experimental measurements, as they are purely auxiliary (most elements were large-scale copies of actual functional elements) and the qualitative agreement is quite satisfactory at this stage. Our library contains elements like splitters, waveguides, mixers and circulators. Based on these devices the integral circuit for investigation of the surface of dielectric bodies has been created. Below, the corresponding elements are presented and discussed in more details. The brief overview of the 3D case, the corresponding problems and possible solutions will be given in the final section.

3. COMPUTER SIMULATION & RESULTS

Some of the following were presented on special conferences [8-10]:

3.1. PBG Waveguide and radiation from the open waveguide

The presented sandwich-like antenna structure consists of the two metallic plates with the dielectric photonic structure located between them. The dielectric area could be used in order to increase electric size and reduce real geometric dimensions of antenna. A periodical structure is formed by the homogeneous distribution of the metallic cylindrical rods inside the antenna volume. Defects are represented by the vacancies – absence of the rod in the given cell. The antenna's feeding is supplied by a coaxial cable and is simulated by the linear current. During the resonant-frequency operation, that is when the wavelength is inside the band gap for the unmodified structure, the EM wave propagates without dissipation along the channel. Moreover,

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there are no significant currents induced on the open end, that could result in radiation in the "backward" direction, so that the far field pattern becomes strictly directed as it can be seen from figure 2a.

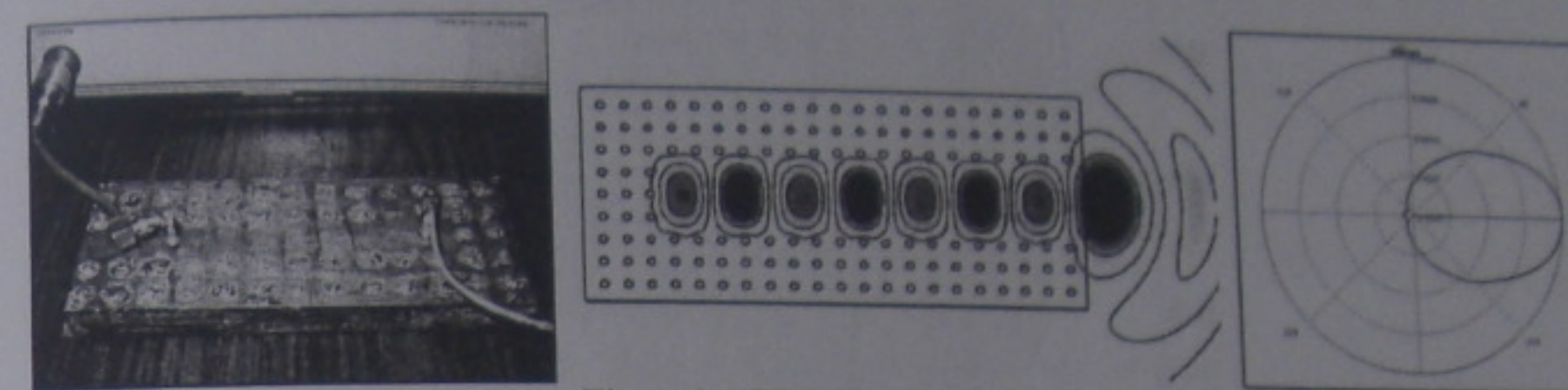


Figure 2a: PBG-based waveguide
large-scale experimental prototype, numerical simulations and far field pattern

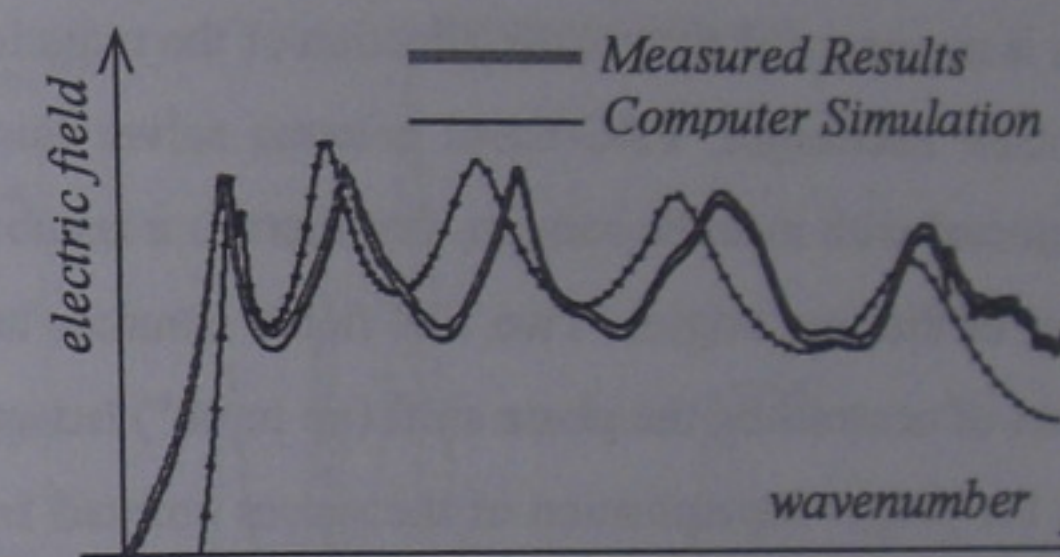


Figure 2b: numerical/experimental verification.

Several control points along the waveguide have been selected for field evaluation. Figure 2b represents the comparison of numerical and experimental values of the electric field in one of these points. As it can be seen from the plot, the results are in relatively good agreement for a wide frequency band (from 1.95 to 3.0 GHz). Though there are serious derivations for low frequencies (long wavelength), the curves show perfect match for short wavelengths.

3.2. Beam-Steering Antenna

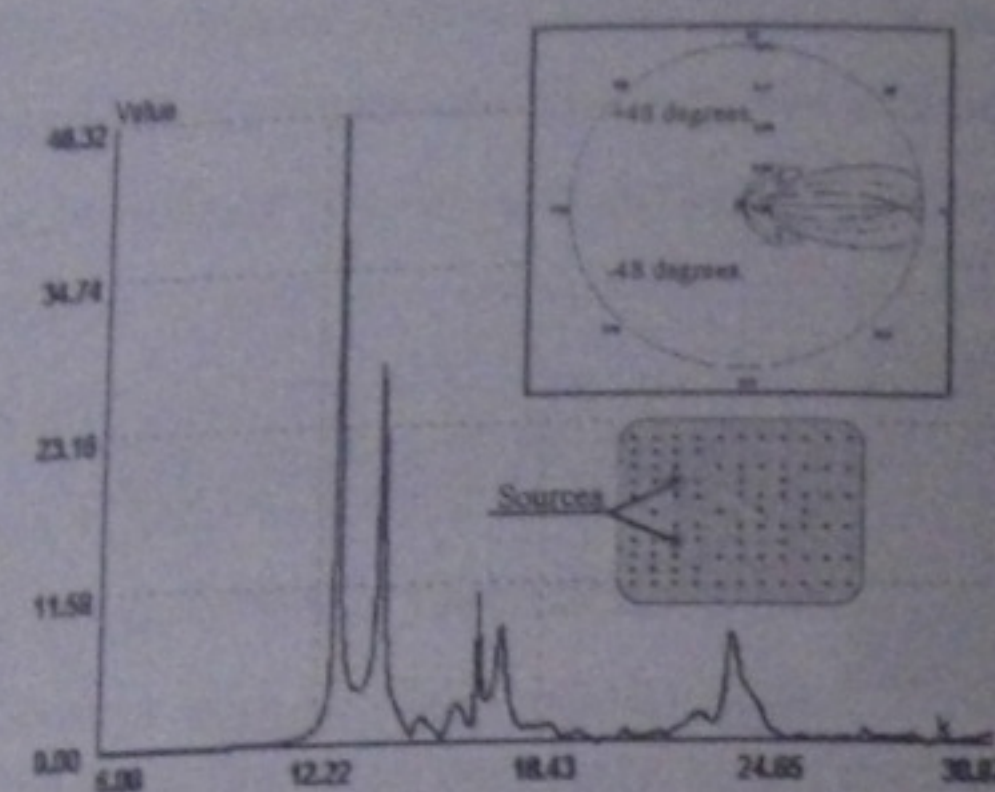


Figure 3: Characteristics of the beam-steering antenna (radiated power versus wave-number), configuration and far field pattern.

In some cases it is necessary to control the direction of the radiation of an antenna, leaving the shape itself unchanged. PBG-based antenna solves this problem: usual dielectric body is injected with metallic rods so, that there is a number of intersecting channels leading out of the two origins. Two EM fields' sources are located in the origins, and by means of controlling the phase shift (up to 48°) between them (Figure 3) one may achieve the proper superposition of the waves emitted from the antennas two open ends of the channels, so that the main direction of radiation in the far field rotates up to 30° . Furthermore, applying signals of the slightly different wavelengths (though, within the band-gap) we may achieve the condition when the beam is periodically rotated automatically, scanning the surroundings. Such antenna is advantageous to mechanically steered antennas, as it does not involve any mechanical movements of its counterparts, eliminating the abrasion and improving endurance. Also such beam steering can be easily controlled and is able to reach faster steering rates.

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3.3. Splitter of the EM Energy

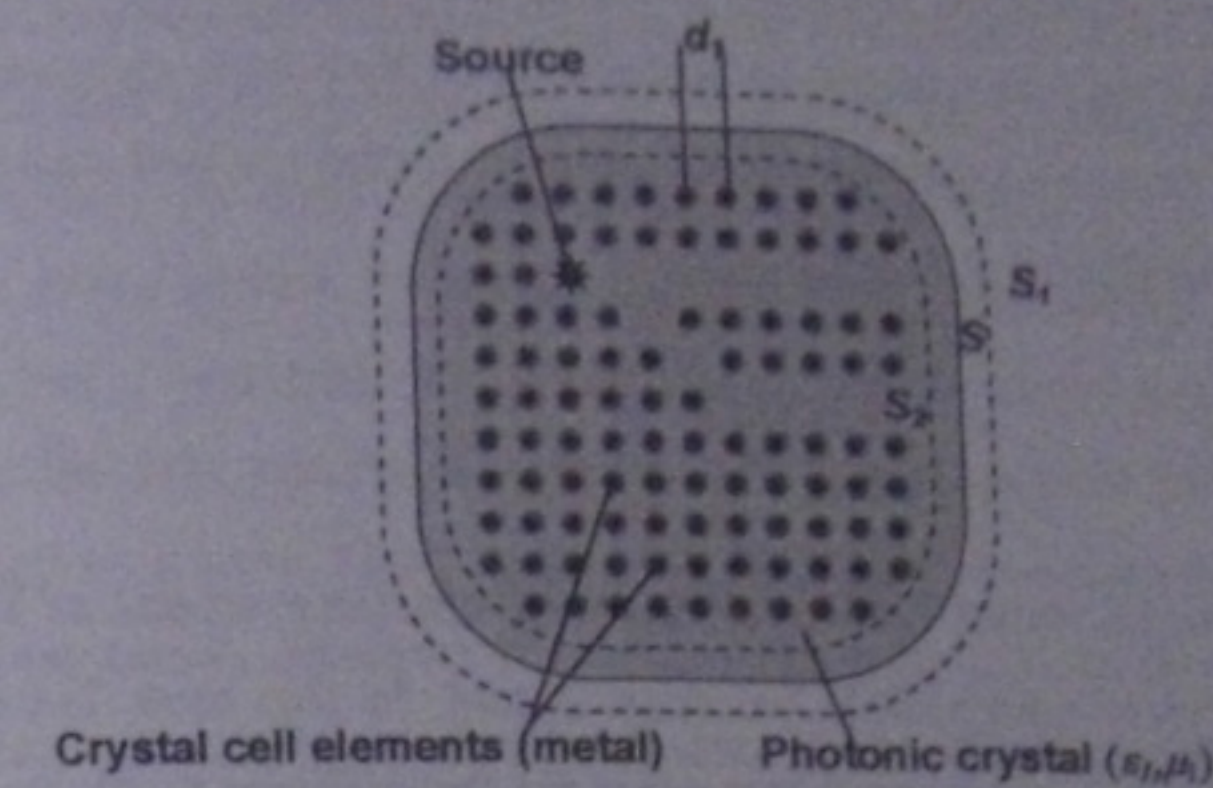


Figure 4. Splitter Model

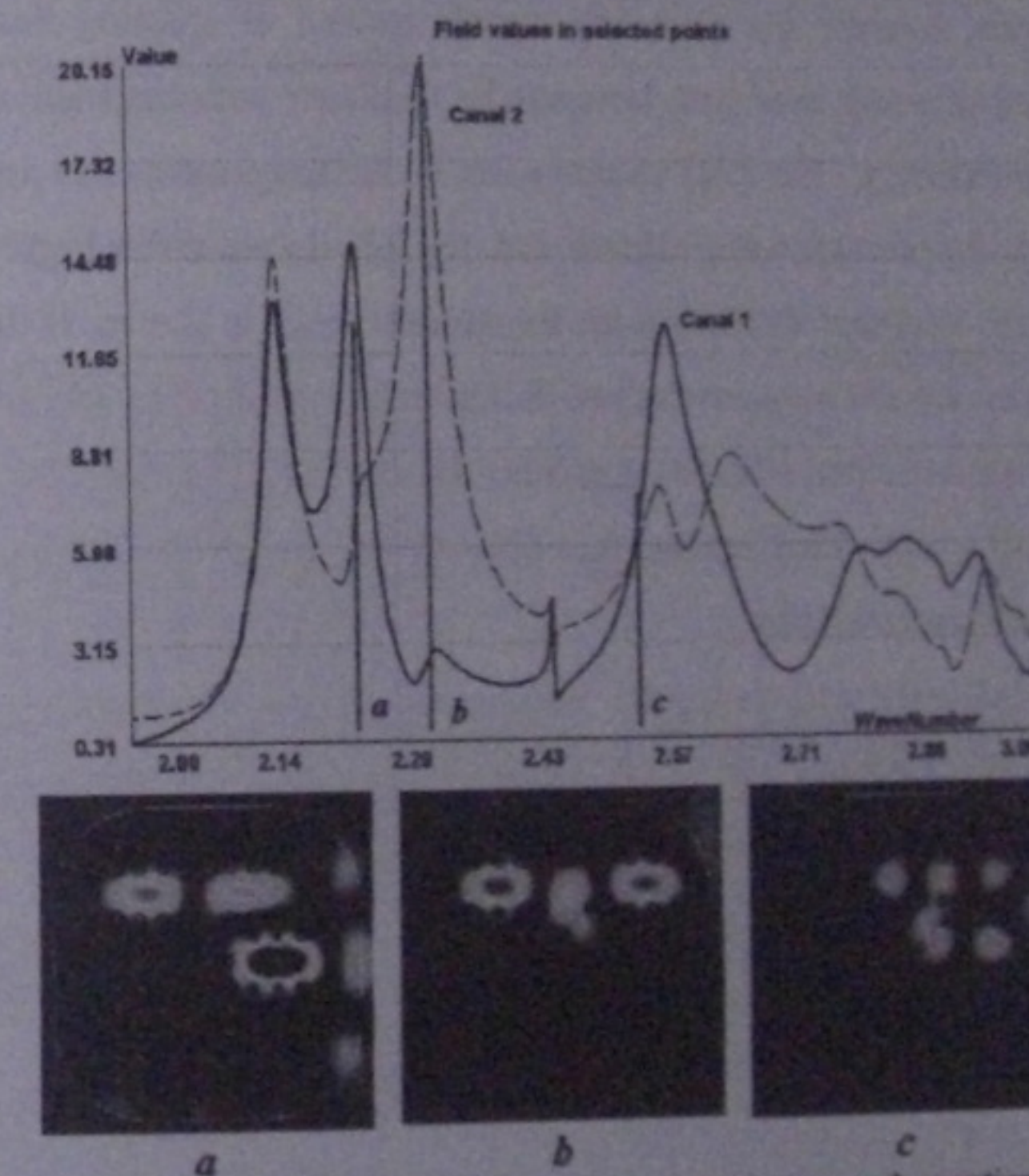


Figure 5. PBG-based mixer (schematic structure, numerical simulations and operation characteristics: dependence of the power distribution in channels on excitation frequency)

The splitter is also a band gap based structure that consists of a periodic structure of certain-type node elements (Figure 4). The EM field source, operating on the band-gap-corresponding frequency is placed inside one of the layers and the channel

leading from this source is formed by removing the consecutive node elements. The channel is split in the way into two subchannels, which exit the structure. By means of altering the operating frequency, allowing, however, it to stay within the band gap, it is possible to control the total amount of power emitted from both channels in wide ranges, effectively directing either the waves, radiated by the inserted source, or any other incoming signal (Figure 5).

3.4. Mixer

In the wide sense of "mixer" we understand the nonlinear effects of EM wave superposition with some intermediate harmonic signal. In this case, however, we consider a device which would be used as a mixer for two different modulated signals but with the *same* frequency. The operation of PBG mixer is nearly same as that of the splitter; however it mixes the incoming signals instead of splitting them into two parts. This kind of mixer must not, however be confused with the traditional mixers used in radio technology. The PBG mixers work on the frequencies that appear within the band gap of the corresponding signals and, though, do not differ highly. On fig. 6 the structure and computer simulation for the sample mixer is shown. If the incoming flux is distributed equally between the two incoming ports (left side, incoming) – 79% of the energy is transmitted (flowing out from the right side), while 17% is reflected from the coupling area. That means, that only 4% of energy is dissipated (that is, penetrates the waveguide walls).

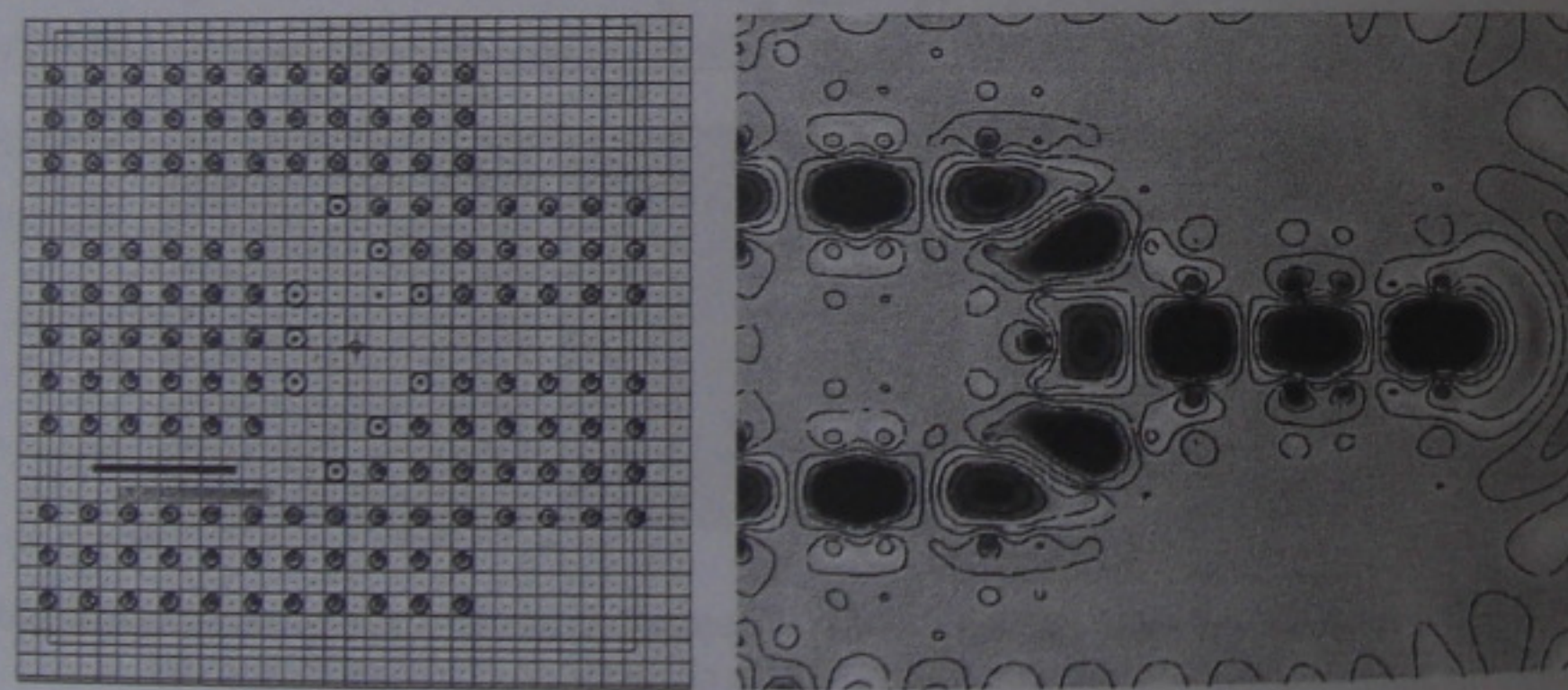


Figure 6. PBG mixer: crystal structure (left) and computer simulation of the electric field (right).

3.5. Filter

The device that filters out the frequencies and sends them into different directions may be easily simulated. Consider figure 7: the two channels are made in the photonic crystal, however they are created by elimination of node elements in different ways. The asymmetry in their geometries and location leads to the unique filtering properties of the system. Of the plot on figure 7 the blue and red lines represent the field in canal 1 and canal 2 respectively. It can be easily seen, that on a certain frequency the field maximum in the canal 1 corresponds to the minimum field in canal 2, and vice versa. Thus, the structure may filter the incoming signals depending on their frequencies. However, such filter will work only in the vicinity of resonant frequencies, and its effectiveness draws down under different modes of operation. The situation is partly saved by the fact, that due to the manufacturing inaccuracies, the resonant peaks are widened and larger frequency domain becomes available (see "manufacturing precision" section).

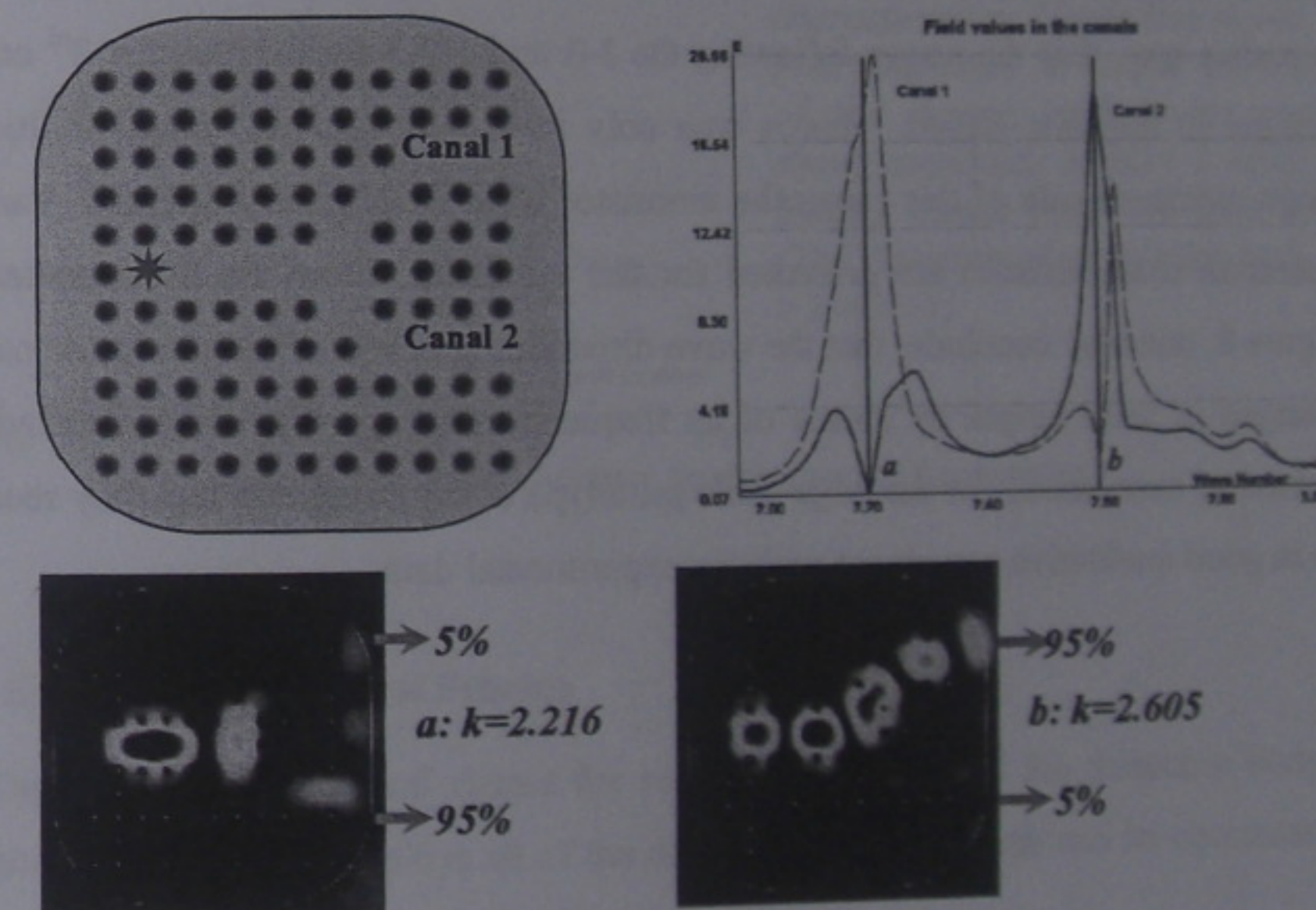


Figure 7. PBG filter: power flux distribution for two peak frequencies.

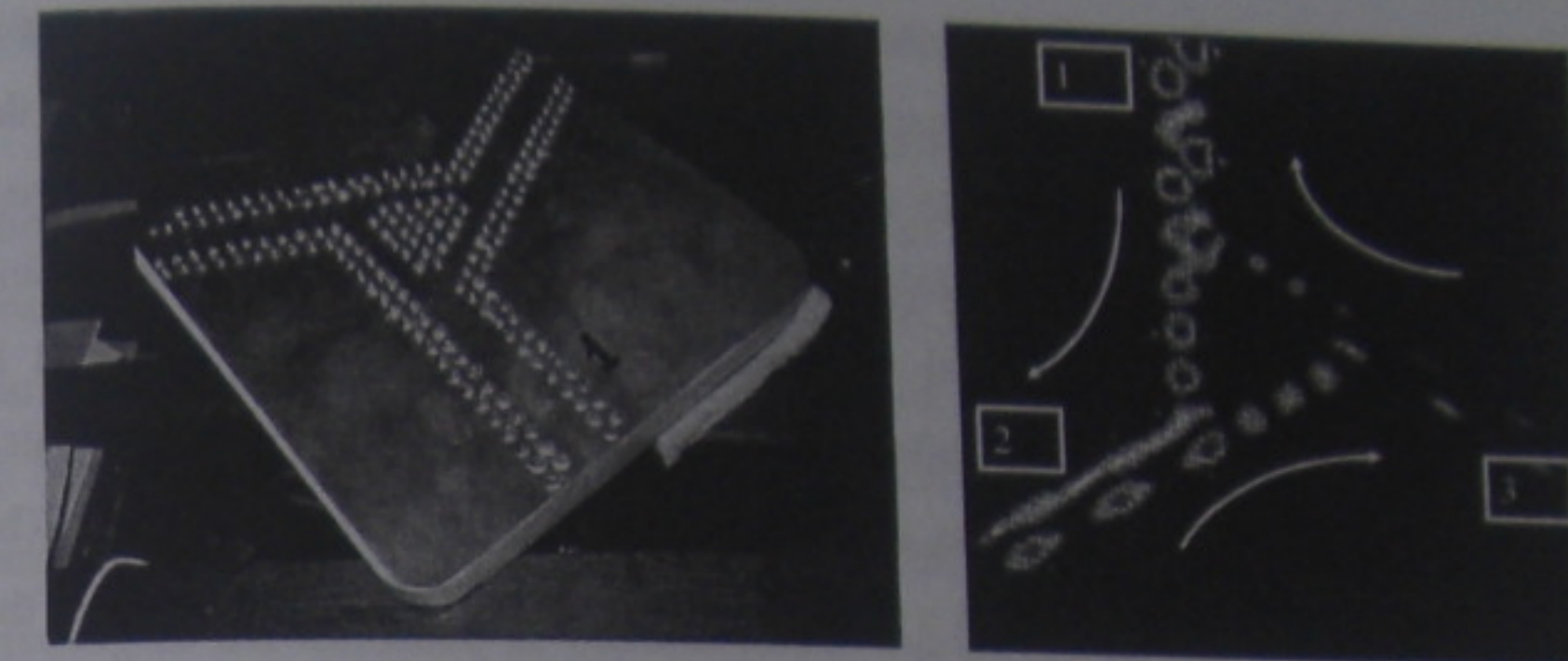
3.6. Circulator:

The circulator is one of the most "controversial" PBG structures (figure 8a). Circulator has three input/output channels and is fabricated in a way, that the normal wave propagation direction is: *channel 1* → *channel 2* → *channel 3* → *channel 1*. Usually, in order to create circulator it is necessary to make use of nonlinear elements, because at the heart of the circulator lies violation of the theory of reciprocity. According to this theory, the wave propagation changes to right the opposite one, once the emitter and the receiver are interchanged.

In our case, it consists of the hexagonal periodic lattice of metallic elements inside the high-permittivity-dielectric and has three incoming/outgoing channels. These channels are connected in triangle inside the structure (see Figure 8).

If the signal is applied to the channel 1, the major part of the power (over 90%) will be emitted through channel 2, rather than 3. We could expect, due to the reciprocity theorem, that if the signal is applied to the 2nd channel, the major part of the power will be emitted through 1st channel, however this doesn't happen. Instead, the radiation peak is for 3rd channel for this case. Of course, there is no contradiction with the theory, because the crucial idea in the circulator is that its sizes are selected in such a way, that the waves following the 1-3 and 1-2-3 paths reach the 3rd output channel in opposite phases. This is true only in a, cooperatively, small frequency range, while outside of this range the circulator loses its special properties. Various operation characteristics are presented for this circulator. From the S-parameters in Figure 8, one may conclude, that the wave-directioning power of the circulator can be changed in wide ranges by means of its frequency selection. We have checked the numerical simulations for the large-scale prototype of the circulator, and they seem to be in good qualitative agreement with the experimental data.

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Large-scale Circulator experimental prototype and numerical simulations

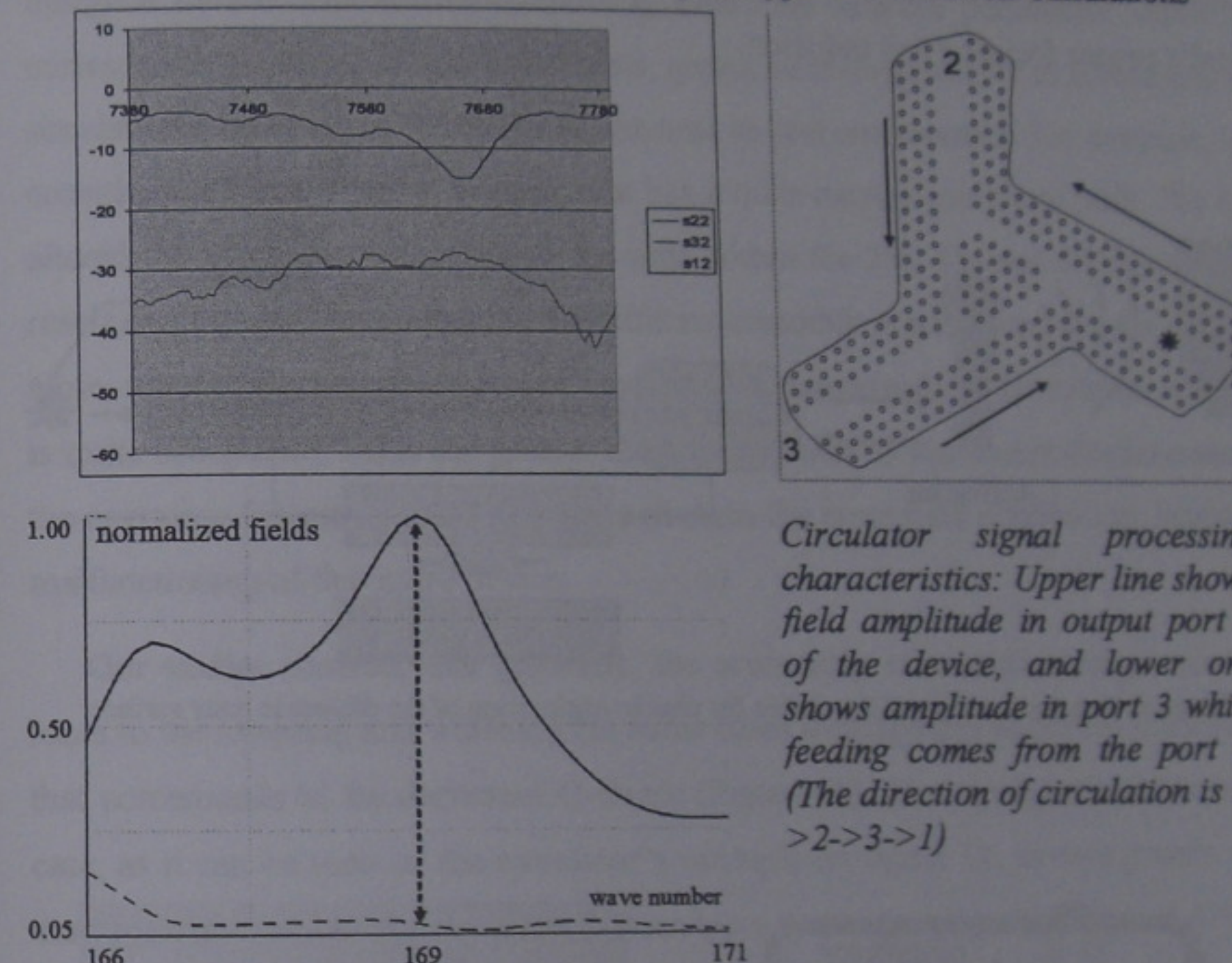


Figure 8. PBG-based circulator. Its properties and S-parameters

3.7. Example of an Integral Scheme

On Figure 9 the integral circuit for remote exploration of the dielectric body's surface is presented. It employs all of the discussed PBG elements and its operation is rather straightforward:

The field from the emitter is split into two signals. First of them - reference signal - is not altered and is forwarded directly towards the mixer. Second one, however, makes it to the circulator, after which it is applied to the antenna. Antenna's EM fields

are incident and reflected from the dielectric surface, carrying the essential information on it. They are then captured by the antenna, and forwarded to the circulator, where they choose the path different from that by which they have arrived. So, at this stage, there is only negligible coupling between the incoming and outgoing waves in the circulator. The signal then moves towards the mixer, where it is combined with the reference signal, after what they both make it to the analyzer which gives us the information of the cracks, stretches or other on the dielectric surface. The actual scheme of the crystal for such a circuit is presented on figure 10. Note, that the dielectric material forms convexities in certain areas, that serve as lenses and help the signal's proper focusing and radiation.

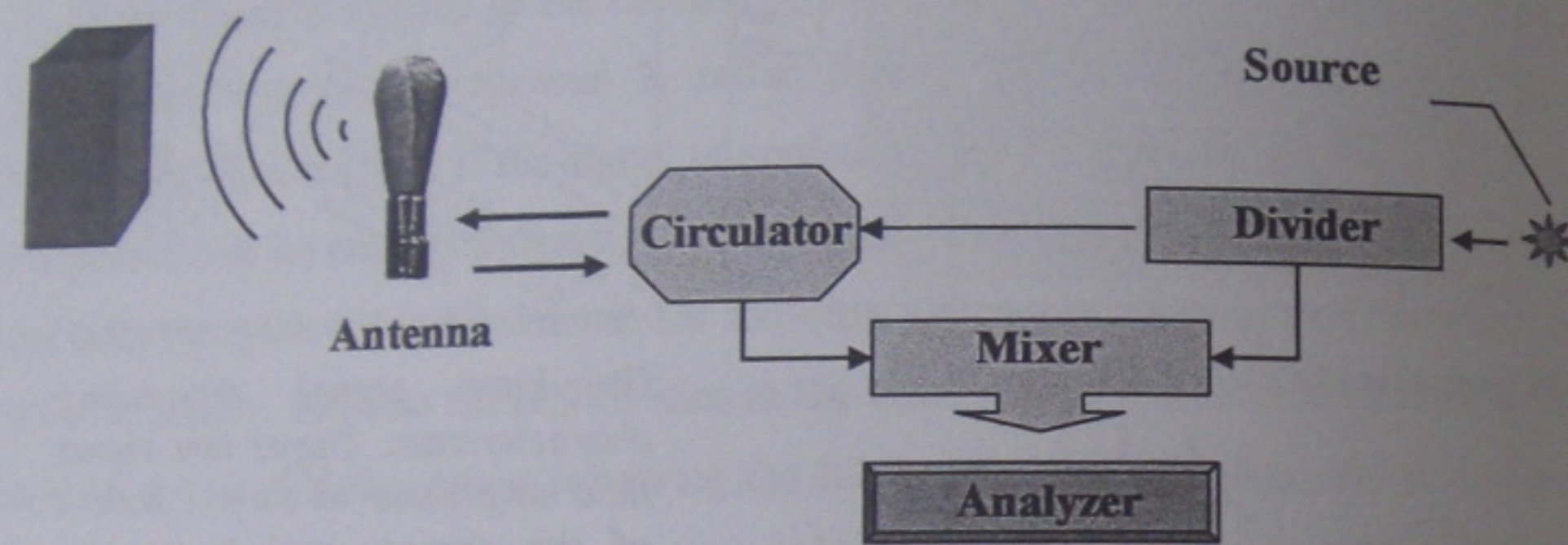


Figure 9. Structural scheme of the device for remote exploration of the dielectric body surface.

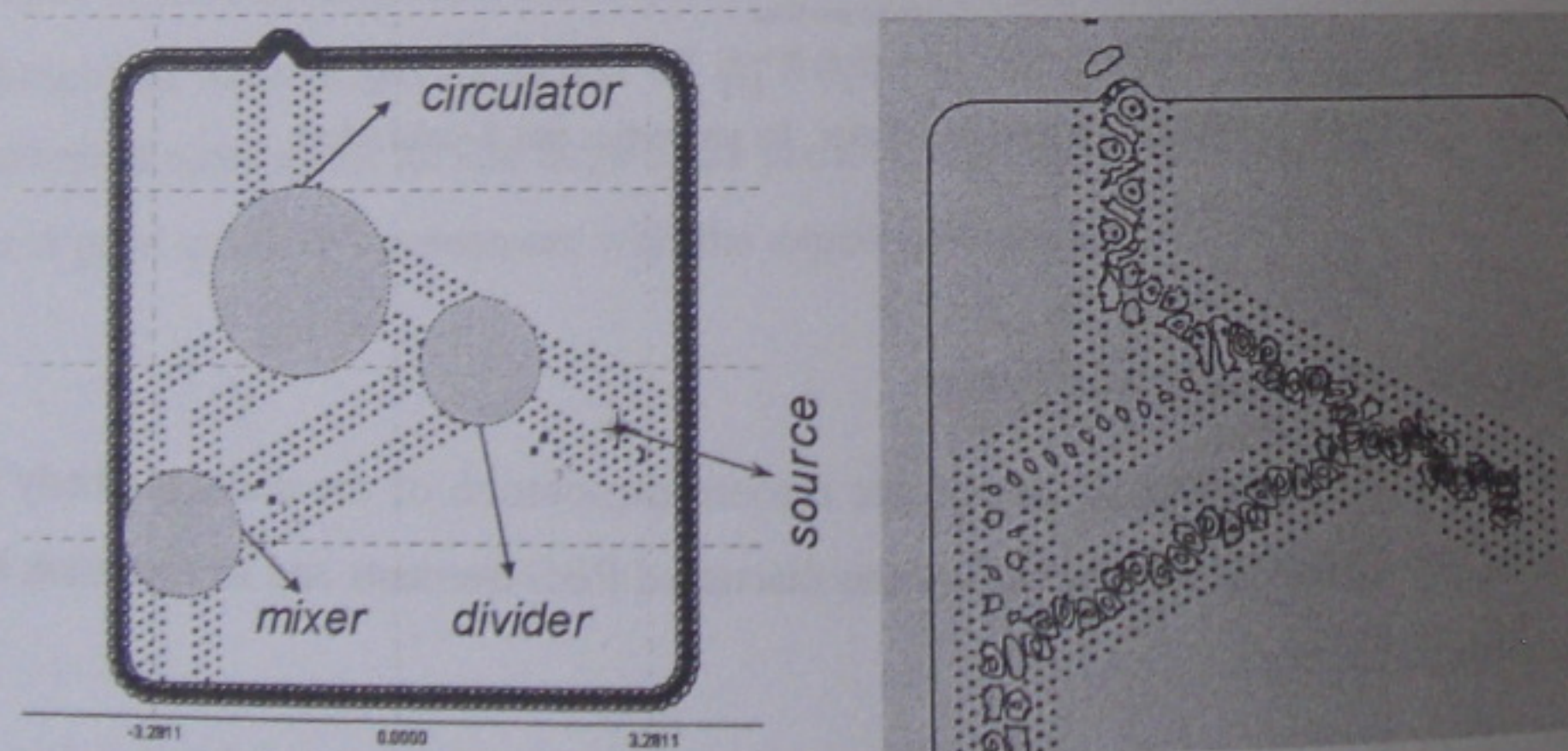


Figure 10: Computer simulation of the integral scheme for remote exploration of dielectric bodies

4. SIMULATION OF MANUFACTURING PRECISION

It is obvious, that during the serial fabrication it is impossible to completely eliminate the manufacturing inaccuracy, such as random deviation in the shapes and positions of the patches, discrepancy between implied and actual electromagnetic parameters of the used materials etc... It is, thus, of economical and practical interest to be able to predict the influence of these uncertainties on the behavior of the finite sample and estimate its overall stability. The algorithm has been developed to investigate the influence of manufacturing inaccuracy on the characteristics of the designed device. The software randomly alters the selected parameters within the corresponding, user-specified, constraints, giving us the opportunity to investigate and simulate the behavior of the device in the near-to-real environment. For example, let's consider the beam steering antenna, that has a quite narrow resonance peak. We have altered the placement and sizes of the rods within the 2%, 5% and 10% limits. The resulting frequency responses for the different assembly precision are shown in fig 11. Note, that that during realization of the device an uncertainty of fabrication up to 5% is quite acceptable, while the greater uncertainty leads to significant displacement of the operating frequency and completely changes the inner field distribution, leading to malfunctioning of the entire device.

Our studies showed, that generally, the accounting of manufacturing inaccuracy leads to the lowering and widening (in some cases overlapping) of the resonant peaks, that corresponds to the decreased Q-factor (Figure 11). Electromagnetic fields in this case, as it can be seen on the circulator's example on figure 12, deviate greatly from their resonant values, and the entire system loses its unique properties. Indeed, 0%-7% inaccuracy does not changes the operation conditions only quantitatively, while ~15% residual brings destructive impact on circulator parameters.

6. FUTURE WORK

In future we plan to extend the abilities of the software to deal with 3D problems. This, however, leads to increased demands to computer resources, that makes the exact solution of a complex problem impossible. The need, therefore, arises in the optimization of the mathematical approach and the new algorithm has to be developed

that will significantly reduce the system requirements and will yield the results with bearable accuracy [11].

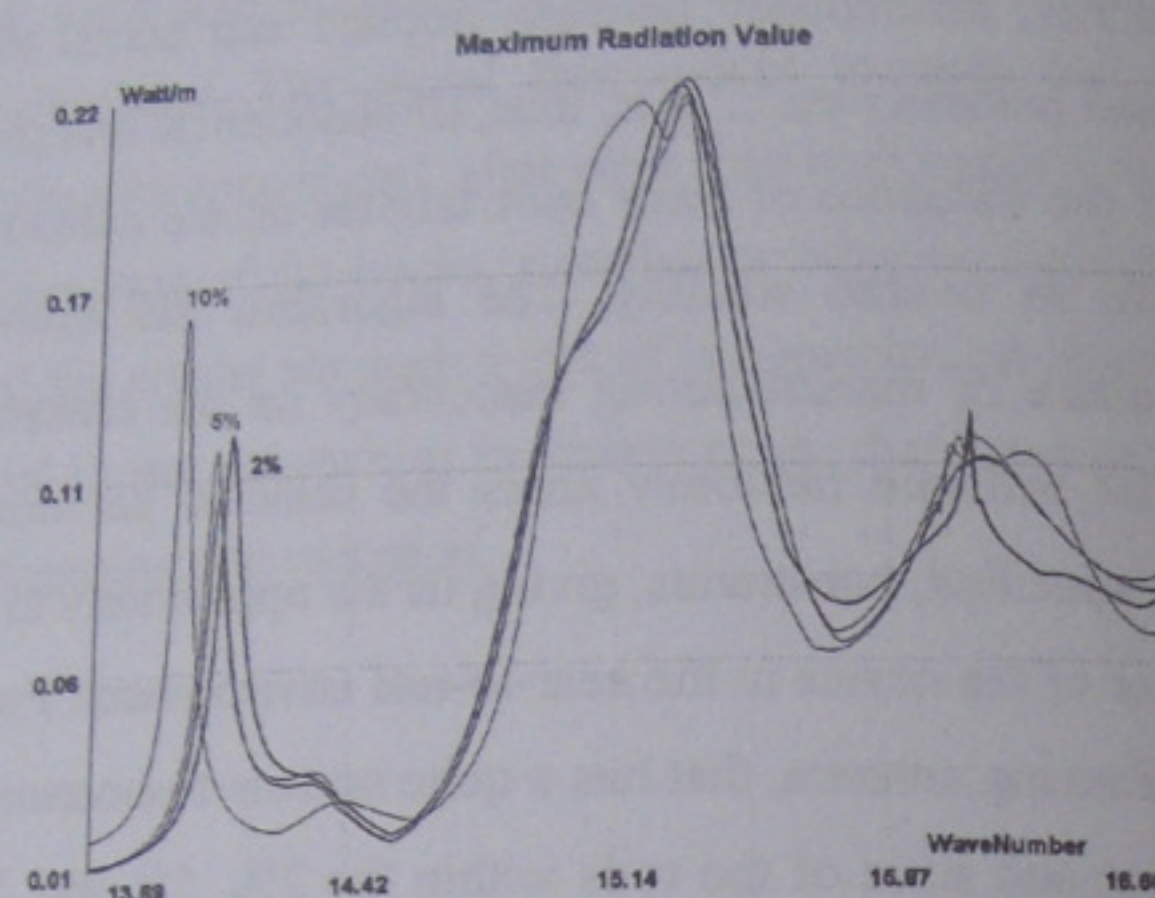


Figure 11. Radiated power versus wave number for the beam-steering antenna, for different ranges of manufacturing inaccuracy.

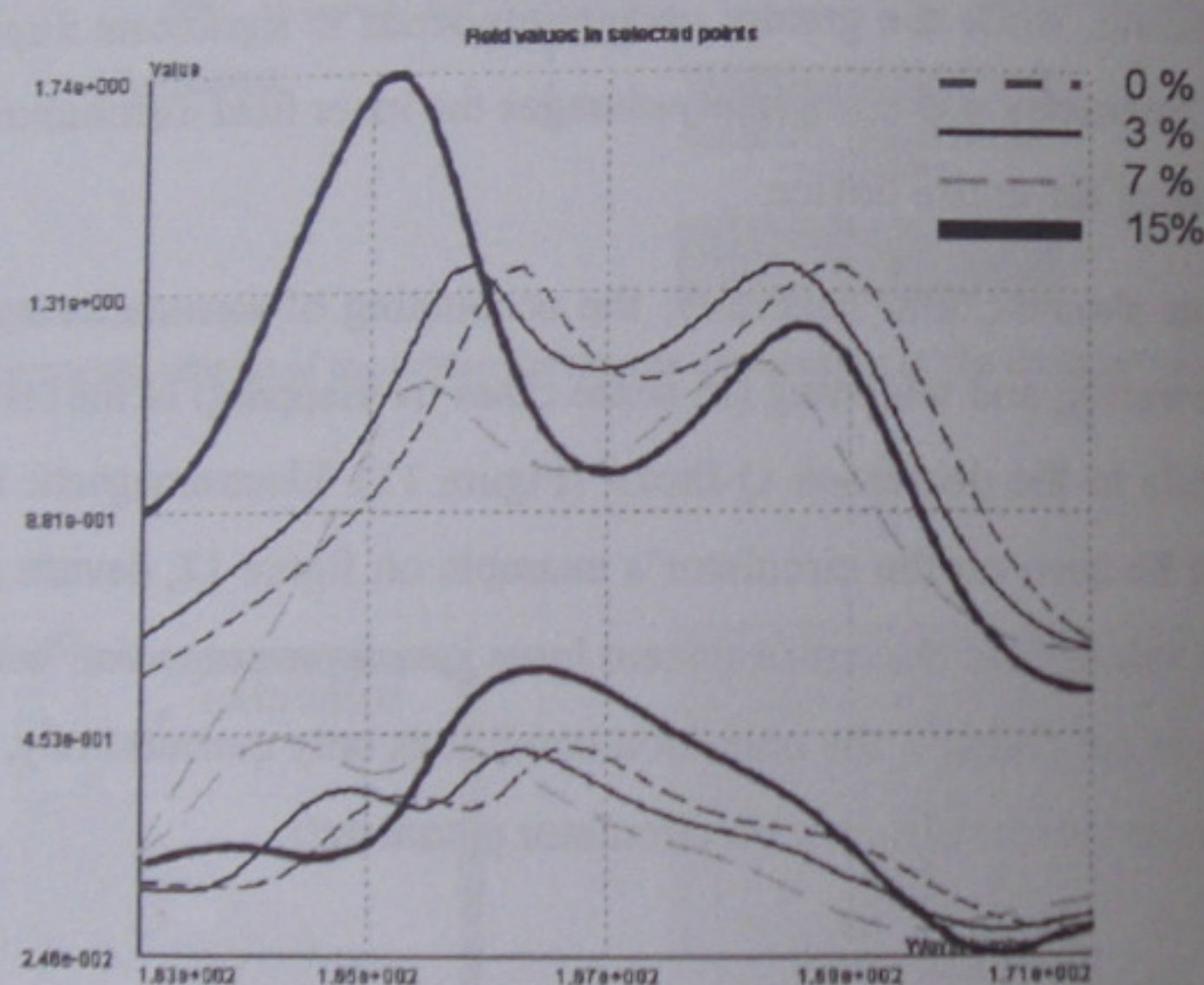


Figure 12. Field values in two different points of the circulator versus frequency for different ranges of manufacturing inaccuracy. If the inaccuracy is greater than 10% the deviation from normal-mode operation is high and the results are unpredictable.

Indeed, in the most generally 3D situation the dielectric crystal is filled with complex-shape node elements. If solving this problem using the MAS approach (other methods come up with the same difficulties), in addition to the geometry-arising

auxiliary sources (that describe the EM fields inside and outside of the dielectric) we need to simulate *each* of the node elements using a separate set of auxiliary sources. For example, if there is a structure of $10 \times 10 \times 10$ metallic helices in the dielectric, and we require around 100 auxiliary sources around each helix wire to accurately simulate it, we would end up with 10^5 unknowns, that would result in 10^{10} -element matrix – already a threshold for modern PCs. Taking into the account that the dimensions of the crystals are usually much larger, we have to develop some effective numerical strategies to simplify the calculations.

One of such simplifications was introduced in [11], and is based on the fact that during the resonant-frequency operation, the fields scattered by each node element may be represented as their eigen-fields for that frequency. This lets us pre-calculate the eigen-response of each element, and use this information to evaluate the effect introducing by this object by using a single unknown variable and satisfaction of the boundary conditions in average, that would represent the normalized amplitude of the auxiliary sources describing it. This approach, however, is rather rude, and implies that all the node elements have the same resonant frequency. Although, it can be used to obtain first estimations for various 3D situations, more accurate and effective algorithm has to be designed and implemented.

6. CONCLUSION

The significance of investigation of PBG devices for modern technologies has been demonstrated. The ability of MAS to solve the complex 2D problems has been proved, the corresponding comprehensive software has been presented and the results of simulations for various electromagnetic functional elements and integral circuits were shown. The fabrication issues and device stability versus manufacturing precision were discussed and the means for their numerical evaluation and prediction were presented. Finally, the transition to 3D problems, the new and challenges arising during it along with their possible solutions have been presented, and the directions for further work have been outlined.

7. ACKNOWLEDGEMENT

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Influence of Specific Absorption Rate Averaging Schemes on Correlation between Mass-Averaged Specific Absorption Rate and Temperature Rise

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Abstract The influence of specific absorption rate averaging schemes on the spatial correlation between mass-averaged specific absorption rate and radio-frequency-induced steady-state temperature-rise distributions in the "Visible Human" body model exposed to plane waves in the 30-800 MHz frequency range is investigated through finite-difference time-domain modeling. The averaged specific absorption rate is computed on the basis of the IEEE Std. C95.3-2002 specific absorption rate mass-averaging algorithm, employing 1-g and 10-g averaging tissue masses and several air-inclusion factors. The analysis reveals that the 10-g average specific absorption rate yields larger global correlation with the corresponding radio-frequency-induced temperature-rise distribution for the considered plane-wave exposures, while the dependence on the air-inclusion factor features a distinctive threshold behavior.

Keywords specific absorption rate, correlation, temperature rise, radio-frequency exposure

1. Introduction

The rapid and widespread penetration of personal wireless communications technology in society has induced a level of public concern about possible health implications of frequent or continuous exposure to radio-frequency (RF) energy. Indeed, RF exposure safety has been the subject of significant research on related dosimetry and possible bioeffects since the aftermath of World War II following the deployment of powerful electromagnetic energy emitters (e.g., radars and tactical radio transmitters), well before the advent of cellular telephony. Likewise, safety standards have been developed by organizations such as the US National Council on Radiation Protection (NCRP; NCRP, 1986), the UK National Radiological Protection Board (NRPB; NRPB, 2004a, 2004b), the International Commission on Non-Ionising Radiation Protection (ICNIRP; ICNIRP, 1998), and the Institute of Electrical and Electronics Engineers (IEEE), which promulgated the first exposure safety guideline in 1966 (United States of America Standards Institute [USAS], 1966) and has issued numerous revisions over four decades (American

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National Standards Institute [ANSI], 1974, 1982; IEEE, 1991, 1999, 2004, 2005), several of which have also been adopted by the ANSI. These standards and guidelines have gone through a maturation process that has recently culminated in the substantial harmonization of the two international RF safety standards with broader world-wide adoption, namely those issued by the IEEE International Committee on Electromagnetic Safety (ICES) and by ICNIRP, recognizing established adverse health effects from possible excessive heating of tissue exposed to RF energy above 100 kHz. As explained in Foster and Glaser (2007), adverse physiological effects or damage to human tissues may be induced by excessive temperature increase following acute RF energy absorption.

The knowledge gathered from the first few decades of RF dosimetry research (Durney et al., 1986) led to defining whole-body and localized specific absorption rate (SAR) limits to protect against excessive core and spatially localized temperature rise, respectively. The SAR is the time-rate of electromagnetic energy dissipation in lossy media per unit of mass (Chou et al., 1996). Because heat is produced as a consequence of electromagnetic energy dissipation, the SAR may be expressed both in terms of electromagnetic and thermal physical quantities as

$$\text{SAR}(\mathbf{r}) = \frac{\sigma(\mathbf{r})}{2\rho(\mathbf{r})} |\hat{E}(\mathbf{r})|^2 \simeq c(\mathbf{r}) \frac{\Delta T(\mathbf{r})}{\Delta t} \bigg|_{\Delta t \rightarrow 0}, \quad (1)$$

where $\sigma(\mathbf{r})$, $\rho(\mathbf{r})$, and $c(\mathbf{r})$ are the medium electric conductivity, mass density, and specific heat capacity, respectively, at any point $\mathbf{r}$, while $|\hat{E}(\mathbf{r})|$ and $\Delta T(\mathbf{r})$ are the corresponding local electric field magnitude and temperature increase. Equation (1) is valid under the assumption of negligible heat diffusion as the time increment $\Delta t \rightarrow 0$. Due to heat diffusion, as well as possible thermoregulatory compensation in living tissue, temperature increase due to RF energy dissipation would normally saturate. Since physiological effects due to RF exposure may be produced by partial or global body temperature increase, linking the SAR and temperature rise is certainly relevant.

For what concerns the localized SAR limits, a standard exposure metric—the mass-averaged SAR—was defined based on 1-g (NCRP, 1986; ANSI, 1982) or 10-g (ICNIRP, 1998; IEEE, 2005) tissue mass. Commonly, the tissue volume used for SAR averaging is taken in the shape of a cube. Therefore, SAR-averaging involves a moving-average of the dissipated electromagnetic energy distribution in all three spatial dimensions, thus yielding a separate mass averaged-SAR distribution (IEEE, 2002) for each chosen averaging mass. The mass-averaged-SAR is an appropriate surrogate for temperature rise, since it features a smoother spatial distribution compared with the point SAR, thus better resembling the smooth temperature-rise distribution. A recent and important development involved the latest revision of the IEEE safety standard (IEEE, 2005), which incorporates 10-g SAR limits that are in harmony with those in the ICNIRP guidelines. However, to date, there is a paucity of systematic studies that address the relationship of mass-averaged SARs with localized temperature rise. Only a small number of studies have dealt with the impact of different SAR-averaging schemes on the relationship with temperature rise. In Hirata and Shiozawa (2003) and Hirata et al. (2006), the correlation between peak mass-averaged SARs, computed using various averaging schemes, and the spatial peak temperature rise is studied in relation to human head exposure in the near-field of dipoles and cell phone-like antennas. Those studies quantify the mathematical correlation between the peak 1-g or 10-g average SARs, employing averaging schemes based on either the IEEE C95.3-2002 standard (IEEE, 2002) or the ICNIRP guideline (ICNIRP, 1998), and peak temperature rise, showing that both 1-g and 10-g SARs

exhibit good mathematical correlation with the peak temperature rise, with the 10-g SAR exhibiting better correlation. This conclusion was based on the correlation between the peak SAR and peak temperature-rise values, as computed in a large number of exposure cases, irrespective of the geometrical proximity between peak locations. Unlike the aforementioned studies, we have investigated the spatial correlation between averaged SARs and temperature-rise distributions for several whole-body plane-wave exposure conditions, studying its dependence on the SAR-averaging scheme. It is expected that such a global analysis of the spatial correlation between very large data sets across several frequencies and exposure conditions allows identifying the SAR-averaging mass that may be considered the most suitable surrogate for RF-induced temperature rise.

The article is structured as follows. The study methodology and modeling aspects are detailed in Section 2. The computational results of the investigation are presented in Section 3 and duly discussed. Concluding remarks follow in Section 4.

2. Analysis Method and Dosimetric Model

The present study encompasses plane-wave exposures of a full human body phantom, suitably voxelized to enable finite-difference time-domain (FDTD) simulations at 30, 75, 150, 450, and 800 MHz. Notice that the well-known whole-body resonance phenomenon (Durney et al., 1986) occurs around 75 MHz. Four exposure conditions have been considered, featuring plane waves impinging on the frontal and lateral (right side) sides of the full human body phantom for E -polarization and H -polarization exposures (Durney et al., 1986). These exposure conditions are schematically represented in Figure 1. A total of 20 exposure cases were considered in the present study—four plane-wave exposure conditions at each of five frequencies. Electromagnetic and thermal simulations were performed using the FDTDLabTM computational suite (Bijamov et al., 2003; Zaridze et al., 2005).

Starting from the computed point-SAR distributions relative to each exposure case, 1-g and 10-g averaged-SAR distributions were subsequently computed on the basis of the algorithm specified in IEEE (2002), further incorporating the following additional provisions:

- expanding the definition of the so-called *used voxels* (IEEE, 2002) by allowing air in the corresponding averaging cube up to a pre-set maximum volumetric fraction

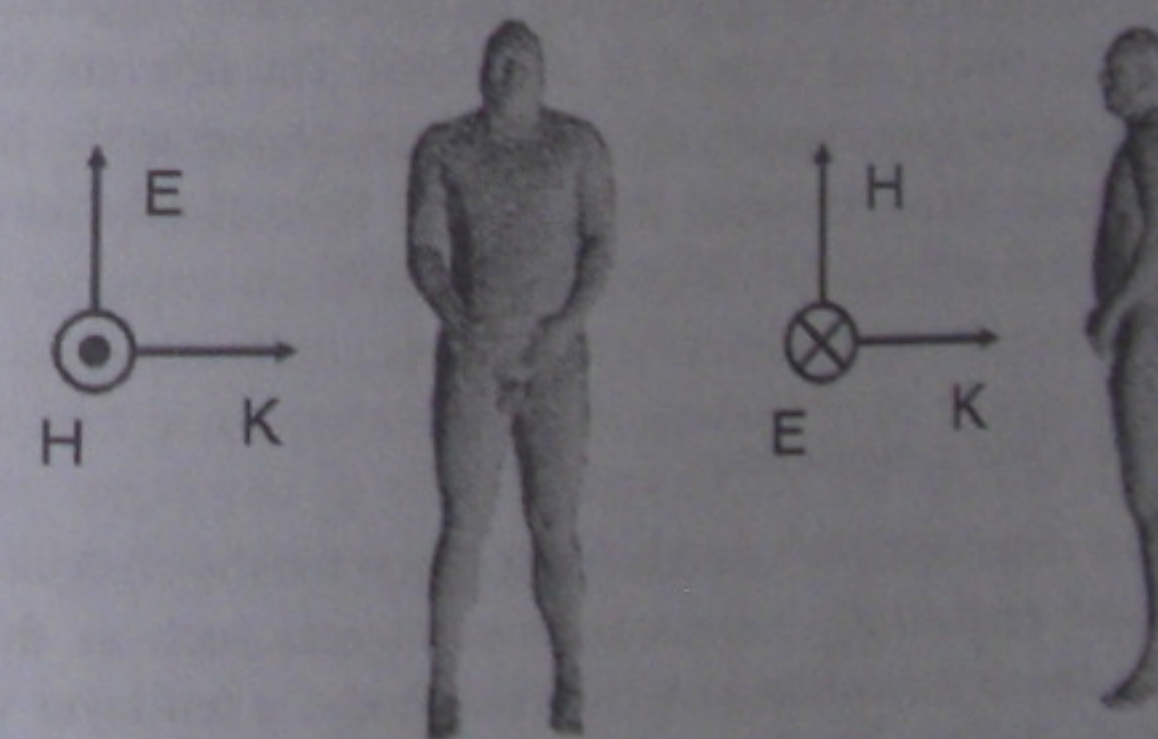


Figure 1. Lateral (right-side) and frontal exposure of the Visible Human model, featuring E -polarized and H -polarized plane-waves, respectively.

- of air (air-inclusion factor, determined by taking the ratio of air volume in an averaging cube and the volume of the cube, expressed in percent); and
 b. not allowing any face of averaging cubes relative to used voxels to be entirely in air.

It should be remarked that these provisions are consistent with the recommendation of 5–20% air inclusion in Caputa et al. (1999) with many researchers' implementations (e.g., Hirata & Shiozawa [2003]) and frequent practice in commercial FDTD codes (e.g., XFDTD™ [Remcom, Inc., State College, PA]). Moreover, they have been recently incorporated in the draft IEEE 1528.1 standard that is presently being developed within the IEEE ICES to enable the use of FDTD computations in SAR compliance assessments of wireless communication devices. Thus the present study also aims at contributing to this standardization effort by thoroughly characterizing the effect of the air-inclusion factor on the whole-body spatial correlation between averaged SAR and temperature rise.

Ten averaging schemes were employed as part of the study, which differ among each other in the SAR-averaging mass (1 g or 10 g) and the maximum allowable volumetric percentage of air in the averaging cube, allowing for 5%, 10%, 20%, 50%, and 75% air-inclusion factors for each averaging mass. Compared to Caputa et al. (1999), we broadened the air-inclusion factor range up to 75% to thoroughly assess its relevance in the SAR-averaging algorithm. A sensitivity analysis of the global spatial correlation between each averaged-SAR distribution in the full-body phantom and the corresponding temperature-rise distribution is finally carried out to determine any parametric dependencies.

2.1. Whole-Body FDTD Model

The full-body numerical model used for RF exposure simulations in this study is based on the Visible Human Project data set (Ackerman, 1998), as further elaborated at the US Air Force Research Laboratory at Brooks Air Force Base (AFB; Mason et al., 2000) to produce voxelized models suitable for FDTD computations that span several spatial resolutions and to define the tissue type and properties in each voxel. We employed the Brooks AFB model featuring 3-mm × 3-mm × 3-mm voxels to represent the anatomical features reasonably well, to satisfy the FDTD stability requirements (Taflove, 1995) up to about 1.0 GHz, and to yield acceptable simulation run-time and computer memory requirements for the aforementioned exposure cases. The model features 40 different tissues with dielectric properties (relative permittivity and equivalent electrical conductivity) based on Cole and Cole (1941) and Gabriel et al. (1996). The relevant tissue properties for thermal analysis (specific heat capacity, heat conductivity, metabolic heat production, and blood perfusion rates) were compiled from several sources (Bernardi et al., 2003; Flyckt et al., 2006; Li & Gandhi, 2006; Hirata et al., 2006).

2.2. Electromagnetic Field Calculations

Presently, FDTD is the most suitable numerical technique for the computational analysis of complex-shaped and realistically inhomogeneous objects such as the human body. To simulate the open space surrounding the exposed body, a ten-layer uniaxial perfect matching layer (UPML; Taflove, 1995) padding was added at the computational domain boundaries while leaving at least 30 voxels (90 mm) vacuum from the air–body interface. This separation was sufficient for accurate simulations as test runs with larger separations

did not significantly affect SAR values. Plane-wave excitation and scattering was modeled by means of the total-field scattered-field technique (Taflove, 1995), implemented in FDTDLab and using time-harmonic excitations. The body tissues dielectric properties employed in the simulations are reported in Table 1.

2.3. SAR Calculation and Averaging Scheme

For time-harmonic fields, the point-SAR at the generic voxel (i, j, k) in the body model mesh is defined as

$$SAR_{ijk} = \frac{\sigma_{ijk}}{2\rho_{ijk}} |\hat{E}|_{ijk}^2 = \frac{\sigma_{ijk}}{2\rho_{ijk}} (|\hat{E}_x|_{ijk}^2 + |\hat{E}_y|_{ijk}^2 + |\hat{E}_z|_{ijk}^2), \quad (2)$$

where $\hat{E}_x$, $\hat{E}_y$, and $\hat{E}_z$ are the electric field phasor components, while σ and ρ are the tissue conductivity and mass density, respectively. The 12-component averaging algorithm (Caputa et al., 1999) is implemented in FDTDLab to determine point-SAR values associated to each voxel in the FDTD lattice starting from the field component values at the voxel edges. As already mentioned, we investigated the effect of ten SAR-averaging schemes, differing in the averaging mass and air-inclusion factor (Table 2). The air-inclusion factor is a relevant parameter, since separate treatment is reserved for tissue regions close to the body surface compared to those located more in depth in the SAR-averaging algorithm specified in IEEE (2002), thus creating a discontinuity in the averaged-SAR distributions in those regions (see Figure 2(a)). By contrast, temperature distributions are necessarily smooth within and across body tissues. As qualitatively shown in Figure 2, relative to E -polarization plane-wave frontal exposure of the Visible Human model at 75 MHz, increasing air-inclusion factors tends to smooth out the averaged-SAR distribution, presumably yielding relatively larger spatial correlation with the corresponding temperature-rise distribution.

2.4. Thermal Calculations

The Pennes bio-heat equation (Pennes, 1948), which allows modeling heat generation and transfer mechanisms, such as heat conduction, blood flow, RF energy dissipation, and metabolic heat production rate, was adopted to compute the RF-induced temperature-rise distribution in the body:

$$c\rho \frac{dT}{dt} = \nabla \cdot (k \nabla T) + \rho \cdot SAR - B(T - T_b) + A_0, \quad (3)$$

where T is the point temperature, T_b is the blood temperature (assumed to be equal to 36.7°C and independent of SAR, which is an acceptable approximation as long as the basal body temperature is not altered by RF-induced heat), k is the tissue thermal conductivity, c is specific heat capacity, B is the blood perfusion coefficient, and A_0 is the basal metabolic heat production rate (also assumed to be independent of SAR). Thermal tissue properties employed in the simulations are reported in Table 3. A convection boundary condition was enforced at the body–air interface:

$$H \cdot (T_s - T_e) = -k \frac{\partial T}{\partial n}, \quad (4)$$

where H , T_s , and T_e denote, respectively, the convection coefficient, the body surface temperature, and the external air temperature (Bernardi et al., 2000; Taflove & Brodwin,