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"mBH", Efficient Device for Measuring Static B-H Relationships of Ferromagnetic Materials

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Abstract

One presents the mBH device for measuring static B-H relationships of ferromagnetic materials, whose functioning model had been developed with the help of ICPE SA. Initially, the measuring principle was presented in the PhD Thesis of eng. P. Andrei [1], but the first physical version of the device had some deficiencies and could not reach magnetic flux densities values higher than 1.8T. Thus, new geometries of the magnetic circuit were proposed, using field concentrators, together with the development of computation programs for the magnetic flux-magnetic voltage relationships of the magnetic circuit branches. The tests on the device confirmed the correctness of the proposed method.

Keywords: measuring the static B-H relationship, magnetic circuit branches

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1. Introduction

Given the importance magnetic materials have in the construction of many types of equipment, the specialists paid a special attention in determining the B-H relationship (BH) of these materials. Most of the equipment used to obtain this relationship establishes the dependence between the time integral of the electric voltage and the current which produce the magnetic field in the studied material. The magnetic field strength (m.f.s.) is proportional to the current, while the magnetic flux (m.f.) – thus the magnetic flux density (m.f.d.) – at a certain time results by adding the electric voltage integral to the value of the m.f. obtained at the previous step. Some important drawbacks can be stated: the propagation of the measuring error form the previous step, the need for an uniform magnetic field in the magnetic circuit which must be entirely made from the measuring material, there is no voltage response at constant m.f.. Usually, one makes a sufficiently fast time variable magnetic field (most often sinusoidal with frequencies higher than 5 Hz). Static relationships cannot be obtained. The best known device is the Epstein frame, which measures BH for different dimension sheets, which form the 4 branches of the magnetic circuit. In order to reduce the errors introduced by the field non-uniformity one uses toroidal samples. Another device is the single sheet tester (SST), preferably with two yokes. The sample composed of only one sheet has the role of making the yoke's reluctance almost negligible. The m.f.s. can be obtained by measuring the excitation current but using a Rogowski coil place along the sheet cancels the magnetic voltage (m.v.) drops from the yokes. Obviously, the magnetic field must be time variable.

2. The measuring device of static B-H relationship proposed in [1]

In [1] one proposes a device and measuring procedure of static BH for ferromagnetic materials, presented in Figure 1.

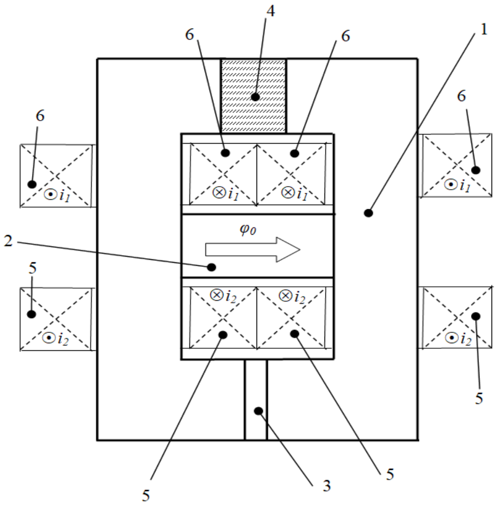


Figure 1. The device proposed in [1]

The device is built from a magnetic circuit (1) with a high increasing magnetic characteristic until a saturation value of the m.f.d. and with a very narrow (negligible) hysteresis. The sample whose BH must be determined (4) is introduced in series with the lower branch. The magnetic circuit has a central yoke (2) with an air gap in which one can place a Hall probe, in order to measure the m.f.d. On the upper branch one can insert a small air gap (3) in order to ensure the stability of the measurements. In the two windows of the magnetic circuit are placed two coils (5, 6) crossed by currents i2 and i1. One feeds coil (5), with increasing values of the current i2, with the step Δi_2. For each value of i2, one searches for the value of the current i1 from coil (6) for which results the null value ($\varphi_0 = 0$) of the m.f. in the median yoke (2).

In [1] is presented a procedure for solving the magnetic field inverse problem such that for each pair of currents $\left(i_1^{(k)}, i_2^{(k)}\right)$ one can determine a piecewise of the sample's BH and the magnetic field from the sample. One had used two programs for computing the magnetic field in nonlinear media.

The first program based on the finite element method (FEM) has the disadvantage of introducing artificial boundaries. The second program treats the nonlinearity through Hantila method [2], [3] and solves the magnetic field problem at each iteration through the Green function method.

In Figure 2 a) and b) are shown the m.f.d. field lines obtained using the two programs.

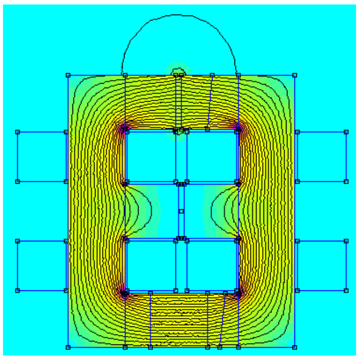


Figure 2.a). M.f.d. field lines in the device with the sample obtained with FEMM

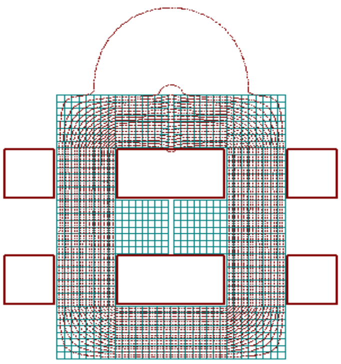


Figure 2.b). M.f.d. field lines in the device with the sample obtained with Green function method

Unfortunately, we have a magnetic field inverse problem on nonlinear media, because the BH corresponding to the sample subdomain is not known. One adopts an iterative procedure for building up the piecewise linear approximated BH. For the first pair of currents $\left(i_1^{(1)}, i_2^{(1)}\right)$ one searches for the slope $\mu^{(1)}$ with whom the linear relationship $H = \frac{B}{\mu^{(1)}}$ starts from the origin such that the m.f. in the air gap of the median yoke (2,3) is null. Actually, one solves the nonlinear equation

$$\Phi_0 = F\left(\mu^{(1)}\right) = 0 \qquad (1)$$

Then, admitting that this linear piecewise of the BH is valid until a value (possibly the maximum) of the m.f.d. $B^{(1)}$, one searches the next linear piecewise of the BH which crosses the point $\left(B^{(1)}, H^{(1)} = \frac{B^{(1)}}{\mu^{(1)}}\right)$ and has the slope $\mu^{(2)}$ for which $\Phi_0 = 0$. The algorithm continues according to the scheme:

$$H = \begin{cases} \frac{B}{\mu^{(1)}}, & for\ B \in \left[0, B^{(1)}\right] \\ H - H^{(1)} = \frac{B - B^{(1)}}{\mu^{(2)}}, & for\ B \in \left[B^{(1)}, B^{(2)}\right] \\ \dots \\ H - H^{(n)} = \frac{B - B^{(n)}}{\mu^{(n+1)}}, & for\ B \in \left[B^{(n)}, B^{(n+1)}\right] \end{cases} \qquad (2)$$

The principle scheme of the device and the measuring procedure had been analysed in papers presented at important conferences and scientific journals [4]-[9].

In [8] and [9] one proposes an interesting device for controlling the null value of the flux through the median yoke. One uses an "O" shaped piece made of a material with a very high dynamic permeability until the saturation point, where the permeability suddenly drops (e.g. Supermalloy). On two branches of the "O" piece one places two coils supplied in sinusoidal voltage (or current), such that the branches of the piece are in the unsaturated zone of the BH when the median flux Φ_0 is null. If Φ_0 has values different from 0, these are added to the fluxes produced by the coils placed on the "O" piece and the BH of the branches increase past the saturation point. If the supply is made in sinusoidal voltage, the current waveform is deformed. Its continuous components, as well as the induced harmonics suggest that Φ_0 is not null.

In the median yoke one can place two field concentrators, in order to increase the control sensitivity of the m.f. Φ_0.

The concentrators do not influence the magnetic field from the rest of the device when Φ_0 is null.

The proposed procedure eliminates the disadvantages of the mentioned classical methods through:

- it is not necessary to produce an uniform magnetic field;
- it does not require samples with special geometry, the BH characteristic can be determined for samples of every shape, the only condition being the existence of plan areas on the sample surface, where the measuring device can be attached, and the dc supply of the device coils produces an attraction magnetic force towards the sample;
- the values of the m.f.d. and the m.f.s. are not measured, but the simple measurement of two currents is made, and an evaluation of the zero value of the flux Φ_0 from the median yoke;
- the measurement of the m.f.d. is not conditioned by its time variation.

Unfortunately, the procedure has 2 important disadvantages:

a) It requires solving a magnetic field inverse problem, because the BH of the sample is unknown. The solving requires a very high computation time, because it involves 3 types of iterations: i) Exploring each segment of the piecewise linear approximated BH, starting from the origin. For the segment (k), one gives the current pair $\left(i_1^{(k)}, i_2^{(k)}\right)$, and searches the slope $\mu^{(k)}$ (in equations (2)) for which the m.f. Φ_0 is null. If we want a BH with an accuracy of K linear segments, K searches are required. ii) Equation (1) is iteratively solved (possibly by the secant method) at each search *k*. iii) At each iteration necessary to solve equation (1), one solves a field problem in nonlinear media.

b) The adopted model for the magnetic field is 2D (plane-parallel). Using a 3D model would require excessively high computation times for the process to be usable. The drastic decrease of the computation time can be done by adopting a magnetic circuit model.

3. Building the "mBH" device for measuring static B-H relationship

The main problems that were solved during the design of the device were due to the existence of technological air gaps that, despite their small size, disturb the correctness of the measurement results. In addition to the use of ferrofluids, the system for mounting the components of the device had been redesigned, so that the technological air gaps are as small as possible.

In order to allow the obtaining of high m.f.d. values in the sample, a shape of the magnetic circuit with variable section that concentrates the m.f. was chosen next to the sample. The cross-section of the columns of the device is $S_C = 20 \times 30\,\mathrm{mm}$, and of the sample $S_S = 8 \times 8\,\mathrm{mm}$. In this way, the m.f.d. in the sample is about 9.3 times higher than in the columns of the device.

Thus, m.f.d. higher than 2.5T can be produced in the sample, without stressing the rest of the magnetic circuit. The used magnetic material was pure iron, with high permeability, as shown in Figure 3.

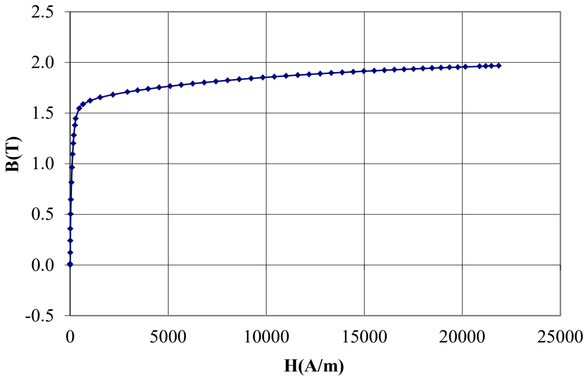


Figure 3. BH of the device's ferromagnetic material

After the mechanical processing, the parts of the magnetic circuit were treated in the ICPE CA laboratories, by the kindness of Prof. Dr. Phys. Wilhelm Kappel. However, before starting the measurements, several demagnetization cycles were performed in order to obtain a very accurate result.

Figure 4 shows the device, with the help of which the BH were obtained.

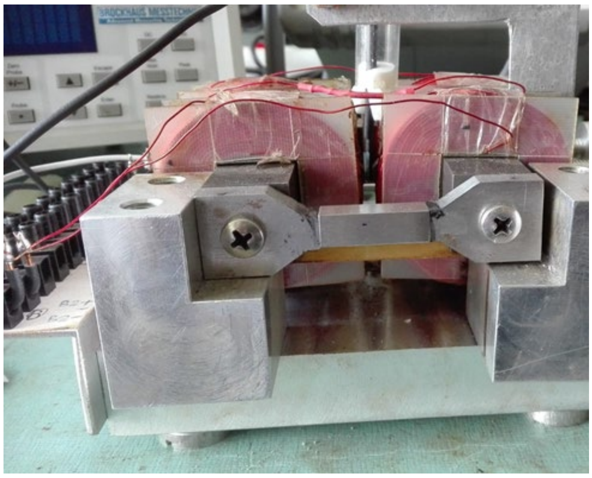
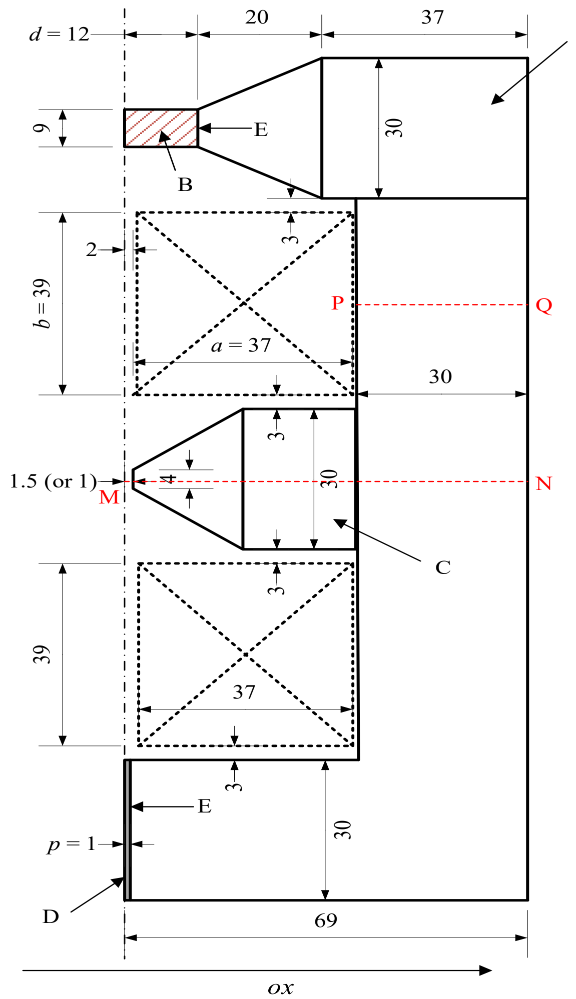


Figure 4. The new "mBH" device

In Figures 5 a) and b), there are presented the execution drawings. We mention that the accuracy of the measurements also allowed the determination of the static hysteresis cycle.



Legend: B. sample with soft BH.
D. auxiliary air gap (can consist of a nonmagnetic material).
E. perfect plane, perfect orthogonal on the *ox* axis and with a small roughness. On this plane one places the device. The central yoke air gap is not necessarily precise.
S. sample field concentrator
C. central yoke and Hall probe field concentrator.

Figure 5.a). The mBH device dimensions (top view).

Due to symmetry, only half of the device is drawn and the branch containing the sample in the upper part

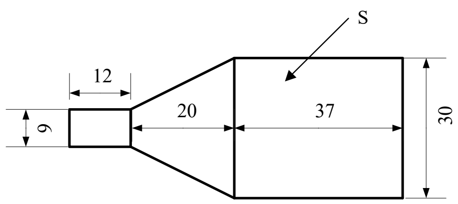


Figure 5.b). The field concentrator (top view)

4. Magnetic circuit branches

To reduce the computation time, the magnetic circuit model was used, but, unlike the one proposed in [1], the $\varphi - u_m$ relationships were obtained by solving magnetic field problems in nonlinear media.

We mention the fact that the precision of the $\varphi - u_m$ relationships obtained for the magnetic circuit branches (m.b.) is very important for the accuracy of the measurements. The m.b. is a domain, as presented in Figure 6, within which the current density is null and which has the following boundary conditions [4], [10], [11]:

(α) on disjoint surfaces, $S_1, S_2 \subset \partial\Omega$, the tangential component of the m.f.s. H is null;

(β) on the rest of the boundary S_0, the normal component of m.f.d. B is null.

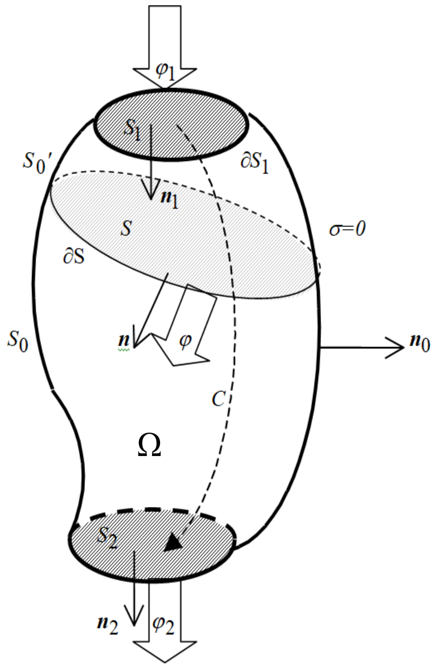


Figure 6. The m.b.

Since in Ω we have $\nabla \times \mathbf{H} = 0$, it results that the scalar magnetic potential V_m theorem is valid. From the boundary condition (α), it results that the surfaces S_1, S_2 are magnetically equipotential. They are called magnetic terminals. We note with V_{m1} and V_{m2} the potentials of the terminals. The m.v. u_m of the m.b. is well defined as being the m.v. on any curve C that connects the two terminals. We have:

$$u_m = \int_C \mathbf{H} \cdot d\mathbf{l} = V_{m1} - V_{m2} \qquad (3)$$

From the boundary condition (β), it results that the m.f. of the m.b. is well defined, as being the m.f. through any cross-section S of the domain: $\varphi = \varphi_1 = \varphi_2$

Four m.b. were defined, analysed by three distinct methods of magnetic field computation.

Branch 1'. It is comprised between the separation surface between the device and the auxiliary air gap and the surface MN (Figure 5.a)), where MN is the trace left by the surface in the 2D drawing. Considering that the m.f. through the median yoke is zero, it can be considered that the surface MN is magnetically equipotential (see also Figure 2). On the 2 sides we have the boundary condition $\mathbf{H}_t = 0$, so $V_m = ct$. On the other 2 branches, which border the m.b. with air, the boundary condition is $B_n = 0$. The $\varphi_{1'} - u_{m1'}$ relationship for this branch is obtained with FEMM (using the "lua" script).

Branch 1". It is defined by the auxiliary air gap. In the absence of the magnetic leakage flux (m.l.f.), the $\varphi - u_m$ relationship is given by the permeance of the branch: $\varphi = \Lambda_m u_m$, where $\Lambda_m = \frac{\mu_0 S_\delta}{p}$, *p* is the thickness of the air gap and $S_\delta = D \cdot L$ is its surface, *L* being the depth of the device on the oz axis. In order to take into account, the m.l.f., one "widens" the auxiliary air gap, with 2 circular arcs (quarters of cylindrical surfaces in 3D), as seen in Figure 7.

Figure 7. The auxiliary air gap branch, with leakages

By imposing the flux φ', so the magnetic vector potential on the arcs of the circle and using FEMM the m.v. u_m is obtained. The environment being linear, one can define the permeance Λ'_m through $\varphi' = \Lambda'_m u_m$.

The difference $\varphi_\sigma = \varphi' - \Lambda_m u_m = (\Lambda'_m - \Lambda_m) u_m$ is the m.l.f. in the 2D model, on the depth *L*. The m.l.f. in the axial direction has a shape similar to that in the 2D plane $\left(\varphi_{\sigma z} = \frac{D}{L} \varphi_\sigma \right)$, so it results the total m.l.f. corresponding to the m.v. u_m : $\varphi_{\sigma T} = \frac{L + D}{L} \varphi_\sigma$, and the total flux is

$$\varphi_{1"} = \varphi + \varphi_{\sigma T} = \left(\Lambda' + (\Lambda' - \Lambda) \frac{D}{L} \right) u_{m2} = \Lambda_T u_{m1"} \quad (4)$$

Branch 1. It is the result of Branch 1' and 1" connected in series and has the relationship $\varphi_1 - u_{m1}$ well-defined, where for a given flux φ_1, the m.v. is $u_{m1} = u_{m1'} + u_{m1"}$.

Branch 2'. It is contained between the surfaces MN and PQ (Figure 5.a)). The relationship $\varphi_{2'} - u_{m2'}$ for this branch is easily obtained using FEMM.

Branch 2". It is the field concentrator, contained between the PQ surface and the separation surface with the sample. The geometry of this side does not allow the use of the 2D model and therefore the use of the FEMM program. The separation surface with the air has the boundary condition $B_n = 0$, and the other two disjoint surfaces have the boundary condition $H_t = 0$. The two disjoint surfaces make it difficult to use the magnetic vector potential to solve the magnetic field problem. Given that $J = 0$ inside the branch, it is much more convenient to use the scalar magnetic potential. On the two disjoint surfaces, where $H_t = 0$, the scalar magnetic potential (0 and a value $u_{m2"}$) is imposed, and on the separation surface with the air, we have the Neumann boundary condition. The nonlinearity of the BH was treated by the Hantila method, using the correction of magnetization M through the value of H. Therefore, to ensure convergence, the permeability of the computing medium μ was chosen with restriction $\mu > \frac{\mu_{d,\max}}{2}$, a suitable condition if we take into account that the magnetic circuit material saturates only in a small area in the vicinity of the sample. In order to obtain the $\varphi_{2"} - u_{m2"}$ relationship of this branch, increasing values of the m.v. are given. For small values, saturation is low, and convergence is fast. The magnetization at the end of the iterative procedure at a m.v. is chosen as the initial value for the next m.v..

Each iteration from the Hantila method is solved by the finite element method, using a tetrahedral network and first order nodal elements, as shown in Figure 8. The computation program is the achievement of this paper's team of authors.

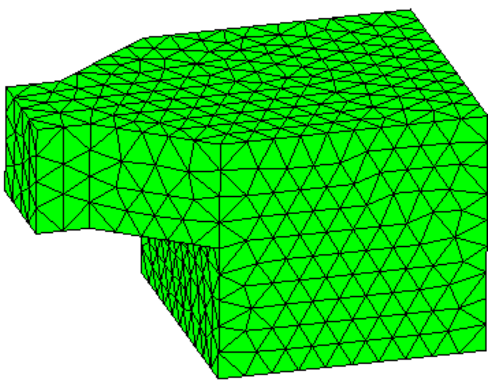


Figure 8. The magnetic field concentrator

5. Determining the B-H relationship of the sample

If the m.f. through the median yoke is null, then the m.v. of this yoke is also null. Coil 5 produces a magnetomotive force $N_2 i_2 = u_{m1}$ and, from the relationship $\varphi_1 - u_{m1}$, it results φ_1. Because the median flux is null, φ_1 also represents the m.f. that passes through the sample. Thus results the m.f.d. from the sample:

$$B_s = \frac{\varphi_1}{S_s} \quad (5)$$

The m.v. of the sample results from the relation:

$$u_{ms} = N_1 i_1 - u_{m2'} - u_{m2''} \quad (6)$$

the two m.v. resulting from the relationships $\varphi - u_m$ of branches 2' and 2''. Then the magnetic m.f.s. in the sample results:

$$H_s = \frac{u_{ms}}{d} \quad (7)$$

where *d* is half the length of the sample.

Figure 9 shows the B-H curves for a sample made of Somaloy 500. We mention that the catalogue curve was taken from the Internet.

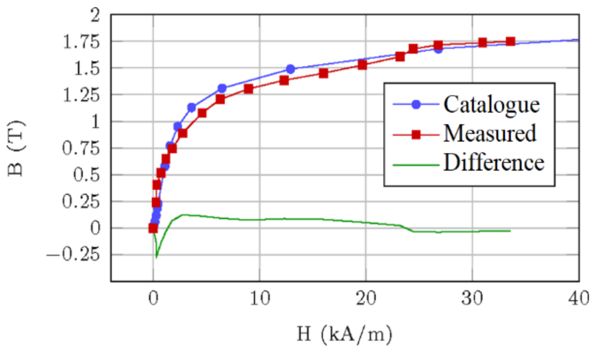


Figure 9. BH obtained for Somaloy 500 [6]

6. Conclusions

The principle and procedure for measuring the static BH, which was first presented in [1], have been developed in this paper. A fast procedure for determining the BH is obtained, based on a magnetic circuit model. We mention that the determination of the $\varphi - u_m$ relationships of the m.b. is done only once, when constructing the device and they are used for any measurement. To obtain good accuracy, these relationships were determined using programs for solving the magnetic field in nonlinear media. The use of magnetic field concentrators allows obtaining high values of m.f.d. in the sample, with a low stress on the material of the magnetic circuit. A better control of the null value of the m.f.d. in the median yoke is also obtained. An important advantage is also the fact that the device can also be used to determine the BH of hard magnetic materials. Samples about five times shorter are used, and field concentrators are lengthened accordingly.

The paper substantially improves the principle and procedure presented in [1].

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