

Design, fabrication and characterization of LTCC-based electromagnetic microgenerators

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Abstract. Design, manufacturing process and properties of electromagnetic microgenerators fabricated in LTCC (Low Temperature Co-fired Ceramics) technology are presented in this paper. Electromagnetic microgenerators consist of planar coils spatially arranged on several layers of LTCC and of a multipole permanent magnet. Two different patterns of coils with 2-, 8-, 10- and 12-layers and outer diameter of 50 mm were designed and fabricated. Silver-based pastes ESL 903-A or DuPont 6145 were used. In order to estimate the inductance of a single spatial coil the Greenhouse (self-inductance) and Hoer (mutual inductance) calculation methods were used. To verify the calculation results a single-layer coil was fabricated for each pattern and its inductance was measured using the precision RLC Meter. Fabricated LTCC microgenerators with embedded coils allow to generate voltage higher than ten volts and the electrical output power of approximately 600 mW at the rotor rotation speed of 12 thousands rpm. The self-made system was used for characterization of LTCC-based electromagnetic microgenerators.

1. Introduction

The paper focuses on design, fabrication and characterization of the electromagnetic microgenerators consisted of planar coils spatially arranged on several LTCC layers and a multipole permanent magnet. Twelve different electromagnetic generators consisted of 2-, 8-, 10- and 12-layers were fabricated using LTCC technology. 28 coils were screen-printed on each layer. Two different layers and silver-based pastes ESL 903-A or DuPont 6145 were used. Diameter of each generator was 50 mm.

Greenhouse [1] (self-inductance) and Hoer [2] (mutual inductance) calculation methods were used to estimate the inductance of a single spatial coil.

The measurement system for characterization of fabricated electromagnetic microgenerators was designed and created. To generate alternating magnetic field a 28-pole permanent magnet was mounted on rotor of three-phase Brushless Direct Current (BLDC) motor. Measurement system included also driver for that type of motor and tachometer [3].

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2. Design and fabrication of electromagnetic microgenerators

LTCC technology allows the fabrication of quite small generators. There were fabricated twelve different types of structures. Each was consisted of several layers of coils electrically connected (through via holes) in one circuit.

The masks for two different patterns of coils are shown in Figs. 1 and 2. There are 28 unconnected coils with connection pads. The single coils are shown in Fig. 3. Width of screen-printed paths was equal to 200 μm , distance between each twists - about 150 μm . To connect the coils two additional layers - top and bottom – were added to connect the coils in series (Fig. 4). The way of connecting the individual layers in 2-, 8-, 10- and 12-layer generators is shown in Fig. 5.

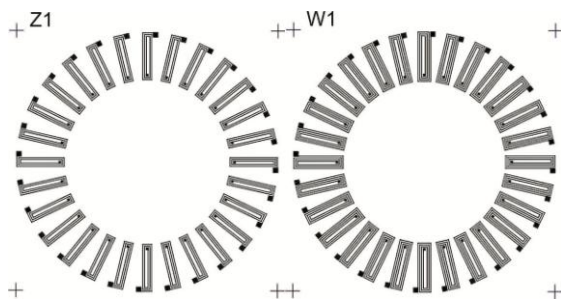


Figure 1. Mask's design of first pattern – 28 coils on the single layer.

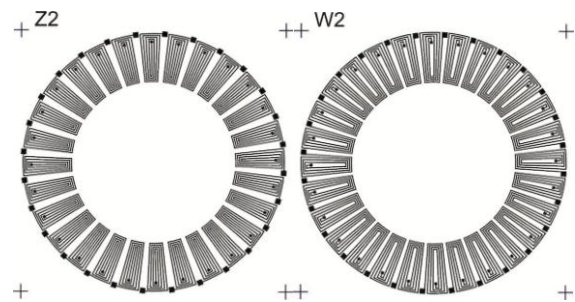


Figure 2. Mask's design of second pattern – 28 coils on the single layer.

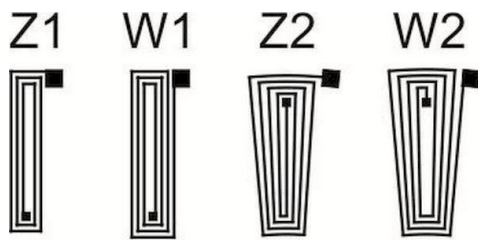


Figure 3. Mask's design – one coil of every pattern.

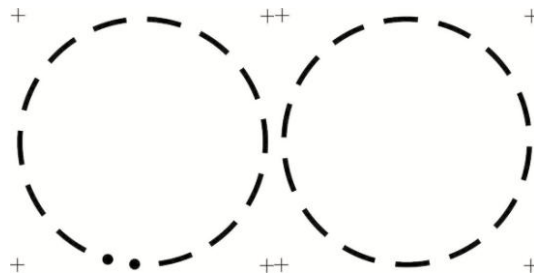


Figure 4. Mask's design – the top and bottom layer.

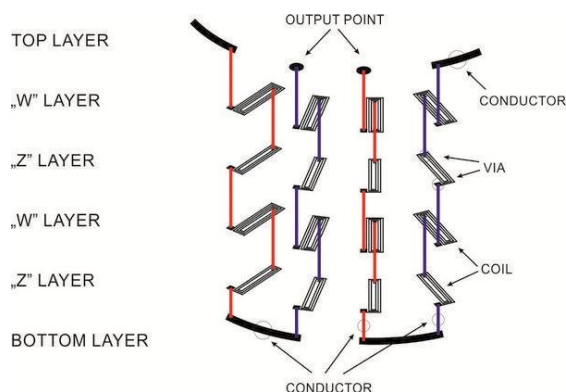


Figure 5. The way of connecting the individual layers.

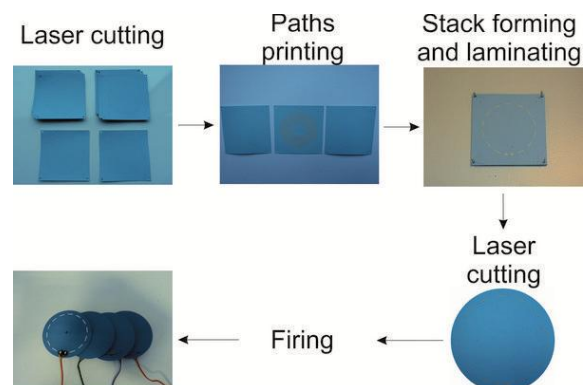


Figure 6. The fabrication steps of the electromagnetic LTCC generators.

The generators' fabrication steps are shown in Fig. 6. Firstly, unfired LTCC sheets (green tape) were cut to the specific size. After screen printing of coils and connection paths (DuPont or ESL, silver-

based ink) proper number of layers were put together and laminated at 200 atm. In the next step the structures were trimmed to a circular shape and fired in the time/temperature profile typical for the LTCC technique [4].

3. The electromagnetic microgenerators' characterization system

The measurement system for testing the electromagnetic generators, presented previously in [3] was modified. New rotating disc with 28 magnets was designed [5]. The disk was fabricated using 3D-printer. Magnets were pressed into holes, than the disc was mounted on the motor's rotor and on the measuring table (Fig. 7). Fabricated coils were screwed to the thread located centrally on the motor's stator. The distance between the coils and magnets was 3.05 mm and it was provided by a spacer made in LTCC technology (Fig. 8).

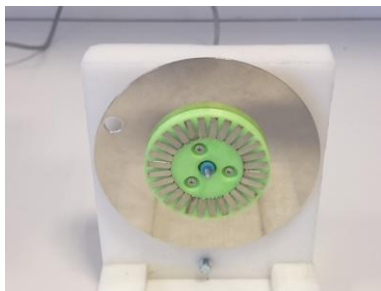


Figure 7. The rotating disc with 28 magnets and the spacer fabricated in LTCC technology.



Figure 8. The electromagnetic microgenerators' characterization system.

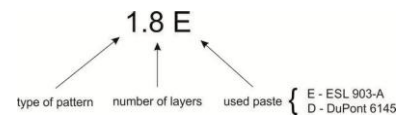


Figure 9. The code scheme used to distinguish the structures.

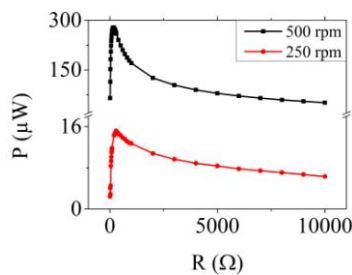


Figure 10. The output power vs load resistance (2.8 D).

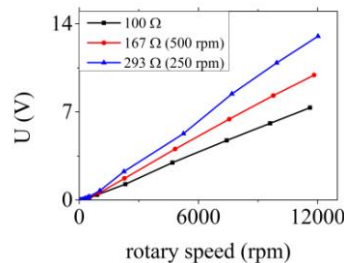


Figure 11. The voltage vs rotary speed (2.8 D).

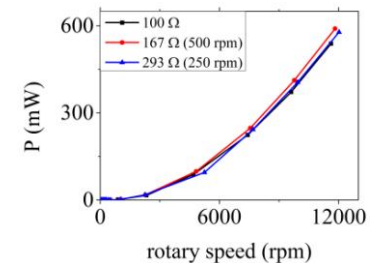


Figure 12. The output power vs rotary speed (2.8 D).

The code scheme used to distinguish different structures was explained in Fig. 9.

For each generator the load resistance for two speeds: 250 rpm and 500 rpm was determined (eg. Fig. 10 – load resistance 293 Ω and 167 Ω, respectively). For determined operating points the characteristics of voltage vs rotary speed (Fig. 11) and output power vs rotary speed (Fig. 12) were measured. Moreover, in order to compare all generators, such characteristics were also measured for the load 100 Ω. During the measurements the rheostat decade was used as the load whereas the voltage was measured by Fluke 8842 multimeter. The voltage delivered by the generator was rectified using a simple circuit with four Schottky diodes (1N5819) and a 1 μF smoothing capacitor.

4. Results

To analyze electrical properties of single coils four different patterns (Z1, W1, Z2, W2) were screen-printed. The thickness and width of the paths were measured using optical profilometer² (Fig. 13).

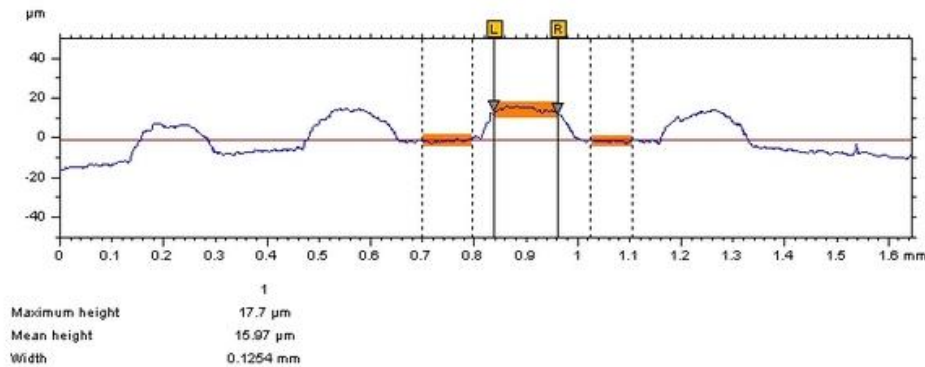


Figure 13. Example profile of W1 coil.

For calculations the average width of paths - 200 μm , average thickness - 16.6 μm and surface resistance 2 $\text{m}\Omega/\square$ (ESL paste) were taken. Resistance was measured using the Fluke 8842A multimeter. Measured and calculated electrical parameters of the single coils are summarized in Tab. 1.

Table 1. Properties of the single coils.

	Z1	W1	Z2	W2
Length of paths l [mm]	46.2	66.0	76.2	80.8
Resistance R [$\text{m}\Omega$]	403	476	680	611
Resistivity ρ [Ωm]	$2.90 \cdot 10^{-8}$	$2.39 \cdot 10^{-8}$	$2.96 \cdot 10^{-8}$	$2.51 \cdot 10^{-8}$
Sheet resistance R_{\square} [$\text{m}\Omega/\square$]	1.75	1.44	1.78	1.51

In order to estimate the inductance of a single spatial coil the Greenhouse [1] (self-inductance) and Hoer [2] (mutual inductance) calculation methods were used. Greenhouse method is dependent on solving inductance equations for planar thin- or thick film coils. Self-inductance must be calculated for every segments of coil. To obtain mutual inductance with Hoer method was need to use a complicated formula which allows determine mutual inductance between rectangular bars. To verify the calculation results inductance of each fabricated coils (ESL paste) was measured using the precision RLC Meter (Agilent E4980A, frequency - 2 MHz). The results are shown in Tab. 2.

Table 2. Measured and calculated properties of the single coils.

	Z1	W1	Z2	W2
Series resistance R_s [$\text{m}\Omega$]	430.78	639.34	576.7	666.75
Series inductance L_s [nH]	56.67	88.56	98.34	114.62
Calculated self-inductance [nH]	52.67	70.01	71.87	77.33
Calculated mutual inductance [nH]	3.03	15.56	19.35	31.10
Calculated inductance L [nH]	55.70	85.57	91.22	108.43

² Taylor Hobson 3D optical profiler available at the Faculty Division of Microsystems and Photonics, Faculty of Microsystem Electronics and Photonics, Wrocław University of Technology.

Also the whole structures were measured and calculated. The results are summarized in Tab. 3.

Table 3. Measured and calculated properties of the structures.

	Agilent E4980A (2 MHz)		Fluke 8842A	Resistance R [Ω] calculated for ESL paste (2 m Ω /□)	Resistance R [Ω] calculated for DuPont paste (3 m Ω /□)
	R_s [Ω]	L_s [μ H]	R [Ω]		
1.8 D	170.04	63.83	97	-	188.50
1.10 D	249.09	94.02	121	-	235.62
2.8 D	329.13	145.70	127	-	263.76
2.10 D	402.34	171.60	125	-	329.70
1.2 E	31.00	6.10	29	31.42	-
1.8 E	173.38	67.89	113	125.66	-
1.10 E	252.05	100.57	144	157.08	-
1.12 E	352.40	140.28	168	188.50	-
2.2 E	37.51	11.31	34	43.96	-
2.8 E	315.10	161.07	142	175.84	-
2.10 E	586.30	265.67	176	219.80	-
2.12 E	1320.00	420.53	248	263.76	-

5. Conclusions

The self-made system for characterization of electromagnetic microgenerators allows to generate an alternating magnetic field and to measure the magnet disc's rotary speed.

The self-inductance of the single coils was calculated using the Greenhouse method whereas the mutual inductance with the Hoer method. Calculated and measured inductance values are very similar.

The generated power is larger for the microgenerators fabricated using the second pattern (Fig. 2). The best output parameters were achieved for 8-layer structure (second pattern and DuPont paste) – 2.8 D. For the rotary speed of 11827 rpm it generates the power of 589.91 mW (for 167 Ω resistance load).

Acknowledgments

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