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CONDUCTIVE TEXTILE TRANSMISSION LINES FOR MICROWAVE FREQUENCY FILTERS

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Abstract: *Smart textiles require transmission of the vital signs towards a central unit, via embedded antennas. Impedance matching is required in order to maximize the power transmitted by the antenna. This paper presents the design and manufacturing of a low pass filter, including a series inductor and a parallel capacitor, manufactured by screen printing on a flexible textile substrate. The filter reflection factor S11 was firstly simulated in the frequency range 5-2000 MHz, then the filter was manufactured by screen printing of silver paste on a Polyamide-imide-Viscose substrate and afterwards measured via a network analyser. The S11 reflection measurement results show a good relation to the simulated values.*

Key words: *silver, smart textiles, reflection factor S11, simulation, measurement*

1. INTRODUCTION

Printed flexible electronics finds nowadays numerous applications in emergent fields, such as wearables, personal protection equipment (PPE) and smart textile materials [1]. Such applications include both the conventional textile functionalities, such as thermos-physiological comfort, mechanical and weathering protection, style etc. as well as various additional functionalities, such as signal transmission via conductive paths, signal transmission via antennas, energy harvesting and storage via e.g. supercapacitors etc. [2]. These smart textiles applications envisage monitoring of vital signs for health and sports [3]. Main aim of the research in this domain is to integrate textile and electronics and to ensure the autonomous functioning of the textronic (textile+electronic) system [4]. Flexible conductive paths are required to transmit high frequency signals within textronic systems. The scientific literature in this field reports various solutions [5-10].

The various additive manufacturing methods for flexible electronics and their advantages are presented in [5]. Some advanced solutions to manufacture microwave passive components and filters on cellulose flexible substrates were accomplished by [6].

A deep analysis of microstrip textile antennas and the environmental factors affecting their performance was accomplished by [7]. The study of high frequency transmission lines with an impedance of 50 Ohm was also done in [8]. The design of a flexible microstrip antenna, including simulation of reflection S11 response both for the strait and bended antenna are presented in [9]. Another type of antenna, namely a flexible dielectric resonator antenna for monitoring vital signs was developed in [10].

The coplanar waveguide (CPW) is a specific transmission line in additive manufacturing, presented numerous advantages, such as single side printing, easy mounting of passive devices and reduced radiation loss [11]. Such CPW transmission lines and the related distributed elements were extensively studied [12], however, the scientific literature of applying CPW lines on flexible substrates is rather scarce.

This paper presents a CPW transmission line, printed on a flexible textile substrate, preliminary designed as low pass filter and subsequently measured via a network analyser for validation of the simulation design.

2. EXPERIMENTAL

2.1 Physical-mechanical properties of the textile substrate

The textile substrate used for additive manufacturing of the silver paste transmission line has the composition of 70% Kermel (Polyamide-Imide) and 30% Viscose, with fireproof properties and a high surface evenness character. The physical-mechanical properties of the textile substrate are presented in table 1.

Table 1: *Physical-mechanical properties of the textile substrate*

<table>
<tr><th>No.</th><th colspan="2">Physical mechanical property</th><th>UM</th><th>Values</th><th>Standard</th></tr>
<tr><td>1</td><td colspan="2">Specific mass</td><td>g/m^2</td><td>268</td><td>SR EN 12127</td></tr>
<tr><td>2</td><td colspan="2">Thickness</td><td>mm</td><td>0,59</td><td>SR EN ISO 5084:2001</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">Tensile strength</td><td>Warp</td><td rowspan="2">N</td><td>1389</td><td rowspan="4">SR EN ISO 13934-1</td></tr>
<tr><td>Weft</td><td>905</td></tr>
<tr><td rowspan="2">4</td><td rowspan="2">Elongation at break</td><td>Warp</td><td rowspan="2">%</td><td>24,6</td></tr>
<tr><td>Weft</td><td>14,0</td></tr>
<tr><td rowspan="2">5</td><td rowspan="2">Tear resistance</td><td>Warp</td><td rowspan="2">N</td><td>66,0</td><td rowspan="2">SR EN ISO 13937-3</td></tr>
<tr><td>Weft</td><td>70,2</td></tr>
<tr><td rowspan="2">6</td><td rowspan="2">Dimensional change at washing</td><td>Warp</td><td rowspan="2">%</td><td>-1,72</td><td rowspan="2">SR EN ISO 6330</td></tr>
<tr><td>Weft</td><td>-1,0</td></tr>
<tr><td>7</td><td colspan="2">Abrasion resistance</td><td>no. abrasion cycles</td><td>28.015</td><td>SR EN ISO 12947-2</td></tr>
<tr><td>8</td><td colspan="2">Air permeability</td><td>l/m^{2}s (mm/s)</td><td>212</td><td>SR EN ISO 9237</td></tr>
</table>

2.2 Determination of relative permittivity and loss tangent of the textile substrate

A test bench was designed to measure the complex relative permittivity of solid dielectric materials. The system comprises the Agilent E4991A RF Impedance/Material Analyser, the Agilent 16453A dielectric material test fixture, and a solid dielectric material sample for measurement. Utilizing this analyser, the complex relative permittivity of dielectric materials can be measured over a frequency range of 1 MHz to 1 GHz. The Agilent E4991A materials analyser determines the impedance (or admittance) of an equivalent capacitor, which is physically formed by the upper and lower electrodes of the Agilent 16453A test fixture, with the dielectric material under test positioned between them. The relative permittivity of the solid dielectric material is then computed based on the measured impedance (or admittance), given the known thickness of the dielectric material between the capacitor plates. The real part of the complex relative permittivity is calculated using the equation:

$\varepsilon_r' = \frac{gC_e}{\varepsilon_0 S}$, where S represents the surface area of the lower electrode, g is the thickness of the dielectric material sample, and C_e denotes the capacitance of the equivalent capacitor. The imaginary part of the complex relative permittivity is given by: $\varepsilon_r'' = \frac{g}{\omega\varepsilon_0 S R_e}$, where R_e is the equivalent resistance or loss resistance. The loss tangent of the dielectric material is determined as the ratio of these two components. The measured values for the relative permittivity and tangent delta are presented in figures 1 and 2. The relative permittivity and the tangent delta of the textile substrate are mandatory parameters in computing scattering values of microwave transmission lines.

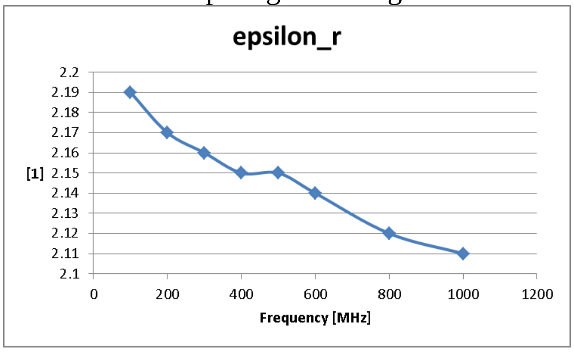


Fig. 1: Relative permittivity

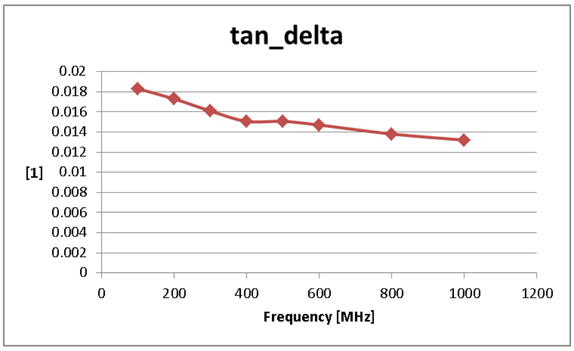


Fig. 2: Tangent delta

Figures 1 and 2 present the frequency evolution of the relative permittivity and of tangent delta for the Polyamide-imide-Viscose textile substrate, used for screen printing of the transmission lines.

2.3 Determination of the thickness of the silver trace

The thickness of the silver trace was determined via the Scanning Electron Microscope (SEM), by averaging the various thicknesses measured crossover the trace. These measurements are shown in figure 3 and detailed in figure 4.

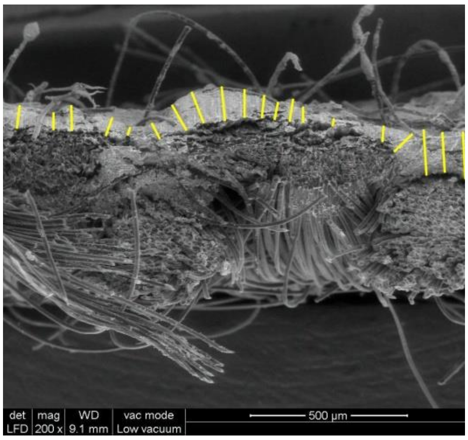


***Fig. 3**: SEM image of the silver trace average thickness*

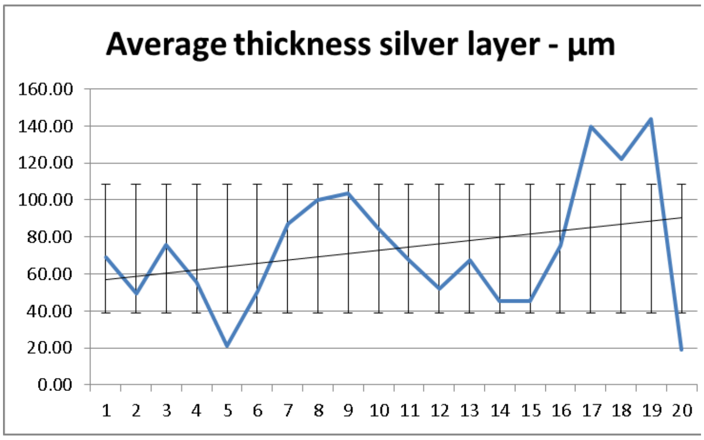
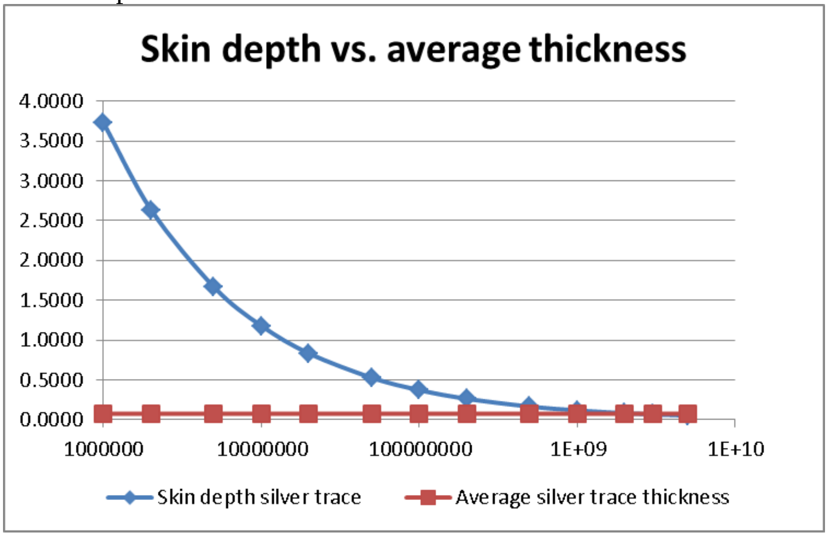


***Fig. 4**: Average thickness with standard deviation of the measured values*

It is recommended for a good CPW transmission line, that the average thickness of the silver trace should be smaller than the skin depth of the silver trace. In our case, the skin depth at 2 GHz is 0.083 mm, while the average thickness is 0.074 mm. Figure 5 shows the skin depth and the average thickness depending on frequency. Up the frequency of 2 GHz, the average thickness is smaller than the skin depth.



The skin depth relation is given by

$$\delta[m] = \sqrt{\frac{2}{\omega\mu\sigma}}$$

Were σ [S/m] – electric conductivity was determined via ohmmeter from the linear electrical resistance

μ - [H/m] magnetic permeability of the silver trace

ω – [rad/s] angular velocity in relation to the frequency of the signal

Fig. 4: *The skin depth in relation to the average thickness of the silver trace*

2.4 Determination of the silver trace morphology

The SEM image (Fig. 6) acquired at 3000X magnification show a porous morphology with large number of pores having the sizes in a range of 2.4 µm, average of 1.0 µm and STD of 0.6 µm. Therefore, the pores are enough small to have a high total boundary area, providing a good electrical contact between the conductive coating and an adhesive layer used to fix the circuit elements on the electric tracks.

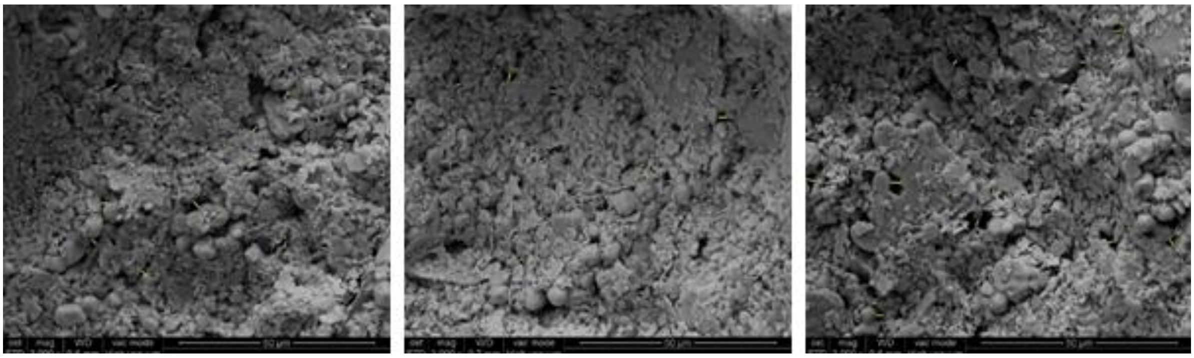


Fig. 5: *SEM images with size measurement bars*

The EDAX analysis (Fig. 6, Table 2) reveals that the Ag is the most prevalent element from conductive ink which forms the active ingredient in chemical bonding with Cl. The other elements are in very small concentrations, excepting the carbon and oxygen which come from the textile substrate.

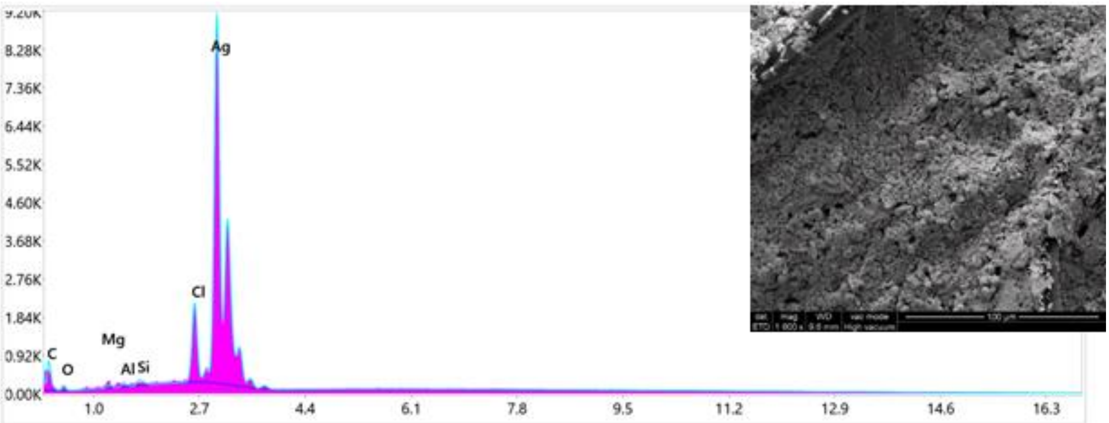


Fig.6: *EDAX spectrum and scan zone at 3000X magnification*

Table 2: *Weight and atomic concentration of elements*

Element	Weight concentration [%]	Atomic concentration [%]
C	9.9	40.5
O	3.8	11.6
Mg	0.6	1.3
Al	0.6	1
Si	0.6	1.1
Cl	6.2	8.7
Ag	78.4	35.9

3. DESIGN, MANUFACTURING AND VALIDATION OF THE CPW LOW PASS FILTER

The CPW transmission line was designed as low pass filter with an inductor in series and a capacitor in parallel. The CPW series inductor has according to the scientific literature a smaller width than the transmission line, while the parallel capacitor has a thicker width than the transmission line. The filter was designed according to the following scheme (Figure 7) and simulated in Sonnet Lite as Coplanar Waveguide (Figure 8).

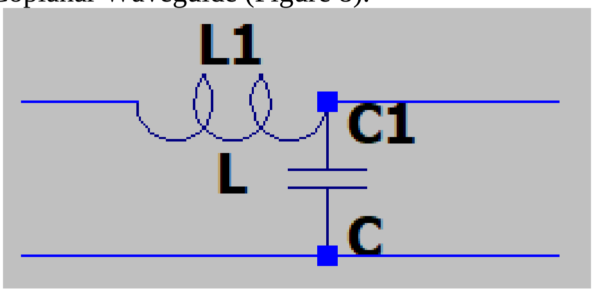


Fig.7: *Design concept of the Low-pass filter*

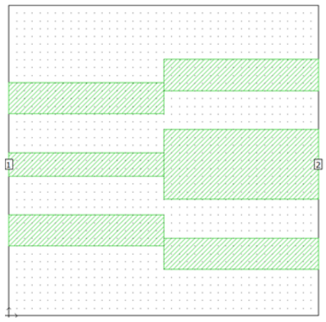


Fig.8: *Simulation of the Coplanar Waveguide including series inductor and parallel capacitor in Sonnet Lite*

The following simulated S11 scatter diagram applies for the CPW Low-pass filter in Sonnet Lite (Figure 9).

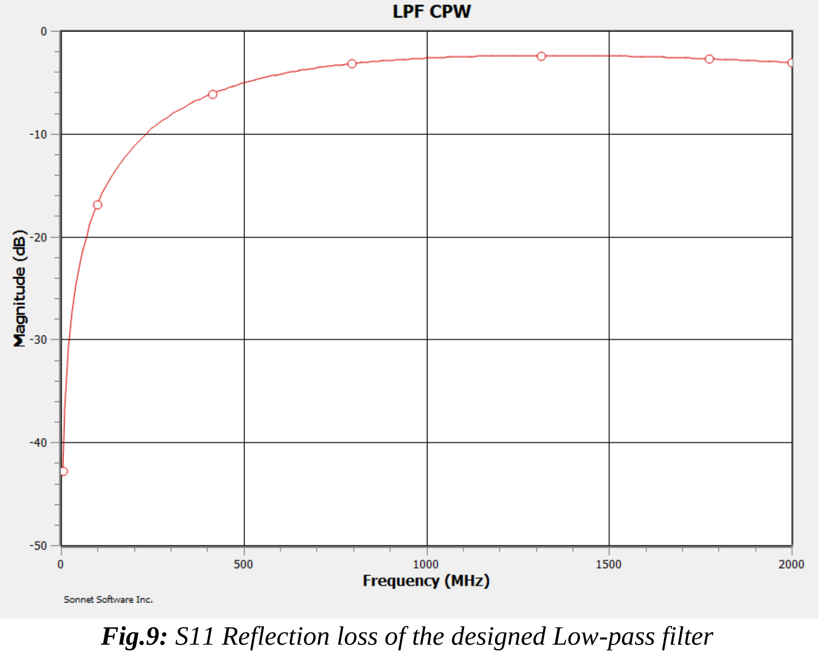


Fig.9: *S11 Reflection loss of the designed Low-pass filter*

After design and simulation the filter was manufactured by screen printing on the textile substrate. Figure 10 and 11 show the manufacturing method of the filter by screen printing with silver paste.

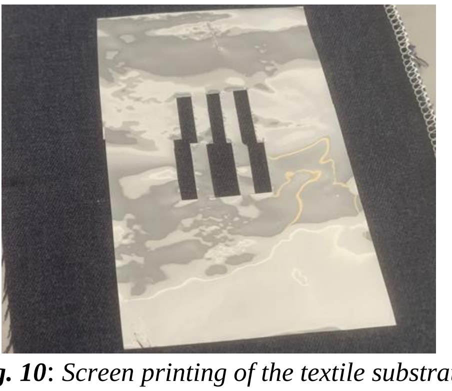


Fig. 10: *Screen printing of the textile substrate*

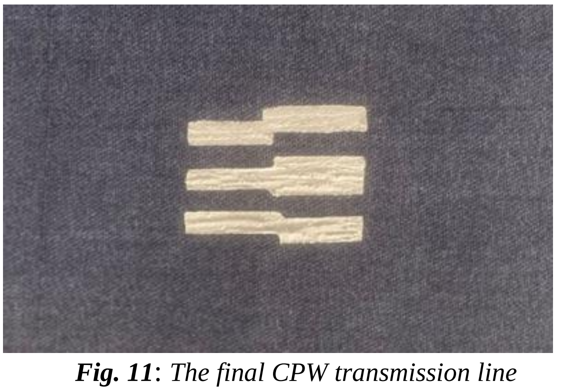


Fig. 11: *The final CPW transmission line*

Figure 12 and 13 present the measurement of the CPW LPF via network analyser in both straight and bended position. The deviation of the S11 signal in bended position had a non-significant deviation to the straight position.

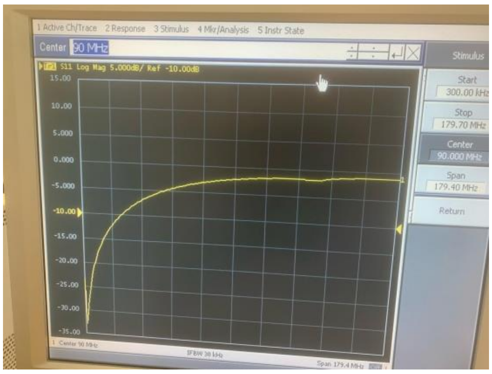


Fig. 12: *Measurement via network analyser*

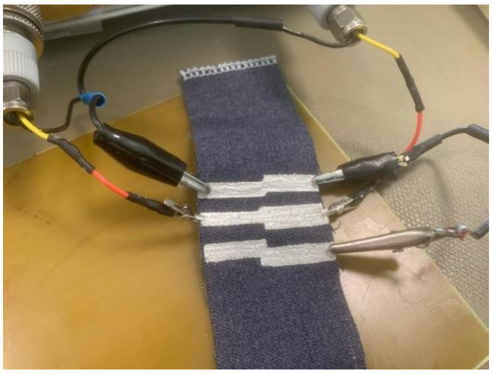


Fig. 13: *Fixture of the flexible CPW LPF for measurement*

Figure 14 present the simulation values of the S11 – Reflection factor in dB, for the frequency range 5-2000 MHz, as well as the measurement of the reflected signal via a network analyser.

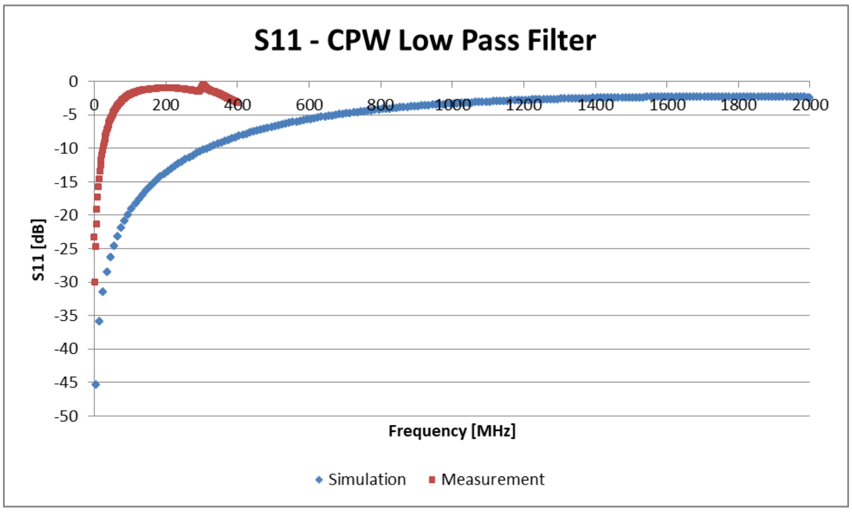


Fig. 14: *Simulation and measurement of the CPW transmission line as low pass filter*

The measurement results show a good relation to the initial simulation for the design of the CPW low pass filter.

4. CONCLUSIONS

The design and manufacturing of lumped components R-L-C on flexible textile substrates via screen printing, opens a promising solution for creation of load matching circuits, destined for embedded antennas in smart textiles. The paper successfully validated a Coplanar Waveguide low pass filter by measurement with a network analyser, after its design and manufacturing by screen printing of silver paste on a flexible textile substrate.

ACKNOWLEDGEMENTS

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