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April 6, 2020

A Review of the doctoral thesis titled
"Textile Integrated Waveguide Components"
submitted by Ing. Miroslav Cupal

Ing. Miroslav Cupal is a doctoral candidate at Brno University of Technology, Faculty of Electrical Engineering and Communication, Department of Radio Electronics, Brno, Czech Republic. He performed his research and prepared this thesis under the supervision of Prof.Dr.Ing. Zbynek Raida of the same institution.

The submitted doctoral thesis contains 79 numerated pages, 7 chapters (preceded by an Abstract and Introduction page), references, lists of figures, tables, symbols, and abbreviations, followed by the candidate's curriculum vitae and a list of the author's publications. The thesis includes 60 references, 72 figures (some of which comprising subfigures), and 8 tables.

Although it has been more than a decade of an increased worldwide research interest in deploying textiles for assembly of flexible and wearable electronic circuits that would enhance the fields of wearable sensors, haptic devices, or body area networks, to mention a few, global research efforts, in spite of the notable advancements, still undergo a rather gradual progress due to inherent technological limitations that have been encountered with it so far. On the other hand, innovative use of standard-, as well as the so-called electronic- textiles, opens up vast opportunities for technological advancements in the upcoming years and a growing market in the niche of smart textiles and smart clothing. In light of that, **the work done within the doctoral thesis submitted by Ing. Miroslav Cupal constitutes yet another relevant research effort and contribution in this context.**

The thesis is organized in six major chapters, three of which cover the three specified objectives of this thesis. Chapter 1 covers the current state of the art that. Chapter 2 declares the *three* objectives that had been set to be addressed by the work on this thesis. In particular:

1) Design methodology, for transitions between a microstrip transmission line (MTL) on a conventional (non-flexible) substrate and a textile (flexible) substrate, will be formulated, with an emphasis on the

transition between two MTLs and between an MTL and a textile integrated waveguide (TIW).

2) A methodology for integration of advanced and reconfigurable microwave components into textile materials will be formulated and demonstrated on the usage of PIN diodes as switches for a reconfigurable circuit.

3) A methodology for the synthesis of a TIW antenna (for the 24-GHz ISM band) will be formulated.

The successive three chapters, namely Chapters 3, 4, and 5 contain the core of this thesis, addressing each of the three declared objectives, respectively. The research results were, in general, achieved by combining a necessary theoretical foundation, typically from the prior art that was pertinent to these objectives, then by 3D numerical electromagnetic models prepared in a commercial CAD, followed by a prototype assembly of the circuit, and measurements of its characteristics.
This approach follows one of modern research procedures to address the subject of research, especially in the case of the electromagnetic structures that do not pertain to canonical scenarios, which is typically faced when dealing with modern electromagnetic circuits, analyses, and optimizations, which are nowadays very much dependent on the results obtained by a trustworthy CAD comprising one of more numerical methods. **The author has thereby demonstrated the ability to independently tackle subtle research challenges.**

Chapter 3 deals with the design of transitions between a textile-based and conventional---substrate-based transmission lines. In outlining his methodology and the solution, the author chooses the theory that is contained in References [53-55] to design the structure and then employs a 3D textile material for the respective part of the overall circuit. The work is continued with numerical simulations to achieve the results for the reflection and coefficients at the desired frequency band (5.8 GHz). A discussion is also made on the solutions obtained by the computational models comprising continuous sidewalls as opposed to the sidewalls based on the stitches (Fig. 4). Parametric analyses then followed to examine the impact of various design parameters on the transmission coefficient (Fig. 5). Following this, a practical circuit was assembled (Fig. 7) and its characteristics measured, completing the analysis within this topic.
(*Note: the reviewer's remarks on this and other topics will be included as an appendix at the end of this report*.)

Chapter 4 addresses the goal of designing and integrating switches within a textile waveguide structure. The analysis begins with a concept of a T-divider that is applied to a textile-based waveguide. The author discusses the options to construct the inductive post (that is being instrumental for the wave power division) within the structure. What follows are comprehensive parametric analyses within which the radius and the conductivity of the inductive post were varied and their effect on the

S_{11} and S_{21} parameters of the given 3-port circuit evaluated. In Section 4.2, switchable pins were added to the inductive post, taking a central location in the circuit and numerical simulations were providing answers with respect to the geometrical distribution of the pins, testing whether a parabolic or a linear (triangular) distribution is more beneficial. Numerical results are provided for the impact of the annular slots that were designed around the inductive pins on the top- and the bottom-conductive plate, and the effect of the diameter of the top- and the bottom- slot on S_{11} and S_{21} parameters around the target frequency of 5.8 GHz. *The result of the analyses showed that the diameters of the slots on the top and the bottom annular ring around the switchable pins are very important parameters, which makes one of the contributions of this thesis.* Lastly, three optional configurations for embedding the PIN diodes within the annular slot around the switchable pins were discussed on the grounds of numerical simulations results. The chapter ends with the textile-integrated waveguide created by screen-printing technology, containing 3 ports and four switchable pins in a parabolic configuration, being loaded with two PIN diodes per each pin, according to Figs. 28, 29, and 24. The three ports also contained an MTL-to-TIW transition based on the Ref. [56]. Although the measured results (Fig. 30) for S_{11} and S_{31} parameters do not quantitatively agree so well with the simulated results (S_{21} parameter has a closer agreement), they fulfill the criteria within the frequency band of interest.

Chapter 5 deals with the circularly polarized textile-integrated antennas for 5.8 GHz and 24 GHz. Although this chapter offers quite a few imprecise, incomplete, or ambiguous discussions (that will be listed later in the appendix of this report), the work within this chapter still encompassed the targeted objectives. Section 5.1 presents the design of the antenna (motivated by the models proposed in Refs. [57-58]), introducing two versions of the antenna model that will be analyzed later in the chapter. It also contains a brief and pretty unclear (in reviewer's opinion) discussion on the coaxial excitation of a TIW (Fig. 34). Section 5.2 analyses the two versions of the design by the extensive use of computer simulations and measurements on the fabricated prototypes. The reviewer also believes the chapter would have been more readable had the part with the manufactured circuits and the respective measurements been separated into another section of the chapter. Nevertheless, the chapter is packed with parametric analyses that were performed using the CAD program, as was the approach before, followed by the prototype circuit assembly and measurements of it. Version 1 (Fig. 53) of the antenna is based on the 3D textile substrate and copper foil as the patch with the sidewalls made of a conductive thread that was sewn through the designated holes around the antenna. Version 2 (Fig. 67) is based on the screen-printed technology using a silver polymer paste over an iron-on foil that prevents penetration of the conductive paste into the substrate, which was a 3D textile in this case. The obtained results matched the CAD-based expectations, in general, except that there occured a resonance frequency shift to a lower value (around 22 GHz) instead of the desired frequency at 24 GHz. The discrepancy was commented on by the author.

Chapter 6 contains valuable information on the characteristics of the materials that were considered for or used in this work, along with the means to specify or measure their values.

<u>Summary of the general remarks</u>
The weaker sides of the thesis are that it lacks clarity in descriptions (text as well as figures) in multiple spots in the text and that it lacks more autor's conclusions and recommendations in the discussions following various parametric analyses. Novelty and originality with respect to prior art should also be better emphasized in some parts of the text. There is also a lack of a standard formatting of figures in which subfigures are typically labeled with small letters within parentheses, which eases readability of text and enables the author more precise referencing to graphical matter within the text. And there is partly a lack of a clear declaration of parameters values related to particular figures in parametric analyses. It is also a bit surprising that the author did not refine the circuit design values and perform another iteration of the prototype manufacturing, in some cases, after the measurements indicated unexpected discrepancy with respect to the simulated results (e.g. as in case of resonant frequency drifting to 22 GHz, instead of 24 GHz in case of the textile-integrated antenna, version 2).
However, the candidate has covered the research topic by showing his acquaintance with the state of the art in this research area and learning from some of the previous solutions resembling the objectives set up for this thesis. He outlined the design concept and presented the specifics of the design models in each of the key chapters of the thesis, which was then followed by an adequate number of parametric analyses, using a commercial numerical electromagnetic code, to provide new findings that are instrumental for the optimization of the circuit, thus giving a practical contribution to this research field. He ultimately applied those findings to manufacture respective prototype models, measured their characteristics and compared to the simulations with accompanying discussions.

The enclosed list of 22 publications in the period from 2016 to 2020, of which in 11 as the first author, shows a dynamic scientific activity of the candidate. Of the topics contained in this thesis in the moment of submitting it for a review, publication [01] has been published in a widely recognized international journal, while publications [02-03] are in the *Submitted* status and in the process of review in the respectable journals. Likewise, publications [04-09] that present portions of this thesis have been submitted to the MIKON 2020 international conference, while earlier pertinent works [10,11,15-17,19] have been published during years 2016-2019. Unless there is a specific requirement of BUT for a pre-defense publishing record of a candidate, **this publication record is**

establishing Mr. Cupal as a recognized researcher and reflects upon his ability to conduct an independent scientific work.

In his doctoral thesis, Ing. Miroslav Cupal presented the results that are relevant for this scientific field and fulfilled the proposed objectives of the thesis in a satisfactory way, while also gaining adequate confirmation of that work by publishing parts of that work at relevant conferences and publishing and submitting to outstanding journals. Taking all into a consideration, **I can recommend this doctoral thesis to be accepted for the defense.**

Sincerely,

[redacted]

Miroslav Joler

Appendix:

- List of remarks to specific details in the thesis

Appendix:
A List of Remarks to Specific Details in the Thesis

For clarity, the list contains the following columns:
page number | item references (figure number, table number, or paragraph number, where applicable) | reviewer's remark.

ch. #	page #	item ref.	reviewer's remark
Intr	1		maybe not a BUT thesis style, but I would appreciate to see some references cited on this page, too, related to various statements (in spite of the Chapter 1)
1	2		I would also appreciate to see references cited with the items of the introductory bullet list.
1	5	Fig. 1	Please check for the copyright policies. I am not quite sure it is enough to just say "Adopted from [26]. Perhaps the copyright holder should be contacted and written permission obtained to include this picture.
3	13		- "...shorting pin is installed in the distance..." >> I suggest write an inline expression for the value of l_w - specify somewhere what software was used for computation - Fig. 3: label port 1 and port 2
3	14	par. 1	par.1: "...transitions simulated with continuous sidewalls..." >> specify in the text **what** was used to make continuous sidewalls par.4: "the larger radius..." >> insert 'the' before 'radius' par.5: "Parametric analyses..." >> insert 'The' before parametric
3	16	Fig. 7	the images are too small. Make them larger and eventually provide images of the sideview, i.e. cross section, of the ISM and UWB case
3	16	Fig. 8	- Rather overlap the curves of simulated and measured S-parameters within a single graph. - Provide a discussion on the presented results and discrepancies between the curves in Fig. 8.
3	17	Fig. 9	- Overlap the respective curves for the simulated and measured S-parameters (and make them distinctive graphically). - Provide a discussion on the presented results and discrepancies between the curves.
3	17		Please state what is your original contribution about this. The original contribution should be better stated.
4	18	par. 5	quantitative parameters of the inductive post are missing. Please add them.
4	19	Fig.10	What is the post conductivity related to Fig. 10?

4	20	Figs. 12, 13	What is the post diameter related to Figs. 12-13?
4	20		I would also appreciate to see the graph with S_{31} parameters, too, to check the symmetry of the network, or the power division ratio.
4	21	Fig.14	- Label the port numbers according to the text. - Indicate what the structure geometry is, the dimensions, the thickness, relative permittivity of the material... Perhaps tabulated or at least as text.
4	21	last par.	- For clarity, specify that port 2 is open and port 3 closed. - Specify a reason for the circular ring slot and make a logical connection to the model in Fig. 14. - Why wasn't the story about the ring slots and Fig. 17 described and mentioned in Fig. 14?
4	22	Fig. 17	The figure is too small.
4	18	Fig.18	Specify port numbers and, preferably, specify which port is open and which is closed, as related to the results following in Fig. 19 and later!
4	23	Figs. 19,20	Within the caption, specify the port number when writing open or close port. - In the caption, check if correct to state "diameter...on the top d_{st} as a parameter"(?)...Its value is indicated in the graph. I guess it should be d_{sb} as a parameter, analogously to captions in Figs. 21-22.
4	25		- inconsistent use of wording for the same thing: 'slot' in par. 1, 'circle' in par. 2, 'ring' in par. 3 >> be consistent in wording, whichever word you choose - par. 2: "...the right diameters..." >>> 'right' is not the best choice of word here...rather use 'proper,' 'optimal,' or 'correct,' to suggest a few - write the manufacturer of PIN diode BAR64-02
4	25		Better explain why we need rings/circles/slots around the pins
4	25	Fig.23	label which equivalent scheme corresponds to ON or OFF state, i.e. left figure ON, right subfigure OFF
4	26	Fig.25	describe that figures are for port 2 being open and port 3 closed
4	27	par.3	distance between the side stitches is missing >> add it into text
4	27	bottom	The last paragraph on the page erroneously contains the caption of Fig. 27 that is on the next page. >> Delete it.
4	28		"The unconnected port was ended by..." >> replace 'ended' by 'terminated'
4	28	Fig.29	Better explain/describe the content of Fig. 29. Include subfigure of the back side of the circuit (or label it if

			present). Explain the connection in the upper left corner of the figure in the middle.
4	29		parasite properties >>> parasitic properties
5	30	par.1	briefly describe the concept of each of the versions 1 and 2 - in words or by figures
5	30	par.4	"First, the TIW has to be designed." >> unclear statement with respect to the next sentence. - "The width of the slot is given **be** the requested..." >> replace "be" by the word "by" - state the relevant expression for the characteristic impedance of the slot (in the above sentence)
5	31	Fig.32	- explain why there is a red line in the sketch on the left side. (That is mentioned later in the text, but it should first be introduced here.)
5	31	Fig.33	- Posts on the right-hand side is not symmetrical to the posts on the left-hand side at the transition from l_3 to l_2. - subfigure on the right: label of the shorter slot reads l_{s2}, while equation (4) has l_{c2}. It should be reconciled which label will be used throughout the text.
5	32	par.1	- "...as a cascade of textile-integrated waveguides..." >>> imprecise and unclear...please refer to proper figure - "The cutoff frequency of the narrower part...cutoff frequency of the wider part..." >>> not clear where exactly to look at >>> rather use labels that were used in the figures
5	32	par.3	- Fig. 34 is not adequately explained. In particular, paragraph 3 does not explain fig. 34. - "...3D textile is usually higher than..." >>> "greater" rather than "higher" - "...conventional transition between TIW...and the coaxial probe is a proper solution." >>> this sentence sounds contradictory. Please check.
5	32	last par.	"The width of TIW is unified keeping the larger width." >>> "larger width" is not precise enough >>> use label from the respective figures to make it clear
5	33	Fig.36	Some dimensions in Fig. 36 (left) are missing: - distance between the lower circle (dashed) and the upper ring - or the radius of the lower circle - and/or the distance of the lower circle from the lower posts - the lower circle is not documented in the figures of the manufactured antenna, nor sufficiently explained or commented in terms of its purpose, placement etc...
5	34		Comment/explain why the ring slot and the cross slot are covered by PEC in the simulations? What is the purpose of it?
5	36	par.1	Why are the phrases "Figure 41" and "Figure 42" typed bold when it is not the style throughout the text?

5	36		"A precise SMA connector is used to excite the waveguide in the optimum position." >> show drawing for better readability "Since TIW meets... (see Figure 34)." >>> unclear sentence, i.e. missing adequate explanation
5	37	par.1	"... is 1.95 mm and the 3D textile 3D097..." >> why not put it in Fig. 32?
5	37		This discussion about the center pin to top wall or not and continuous wall vs. pins and waveguide port is not clearly explained in the thesis!
5	37	Fig.43	explain what is the difference with respect to the conditions in Fig. 39
5	39	Fig.46	With respect to Fig. 46, it would be desirable to include in the discussion which value is your "choice"! So, not just telling what can be read off the figures, but to make a stance on which value you consider best.
5	40	Fig.47	Analogously to the above comment: which value does the author "recommend" and considers best.
5	42		"Now, let us turn the attention to the full model..." >>> why is the antenna simulated separately from the full model in the first place? - I think it would be more readable if this part were written under a new section.
5	43		At this point, I must notice that there are too many similar graphs in the text, yet without clear enough a distinction within the text (and respective captions) on what the difference in the simulation scenario and the simulated structure is!
5	46	par.4	"In this simulation, no foil separating the conductive (screen-printed) surface and the textile substrate was considered." >> unclear sentence. Please refer to some earlier figure or page.
5	51	last par	What type of the thread is used here? The info is missing.
6	54	par. 1	"...there are three main conductive objects to be characterized: textile substrates,..." >> the word "conductive" does not fit here because substrate is not a conductive object.... try with some other word, like "structural objets" or similar
6	56	last par.	Bekonix VN 12.3.2.175S is stated in the first sentence of the paragraph and then again in the sentence starting with "Other two stainless-steel threads..," which does not make sense.
6	57	par.2	"The SIW was designed..." >>> please check if it is correct, or you rather meant to say "The TIW was designed.."
6	57	last 2 par's	- "SIW was not optimize..." >>> insert 'd' at the end of 'optimize'

			- "The cutoff frequency was s 5 GHz." >>> delete 's' - "The simulated SIW manufactured..." >>> insert "was" after "The"
7	60	par.3	- "In the thesis, attention is turned to vehicular applications (cars, busses, airplanes)." >>> we did not see much of this in the descriptions of this thesis! - "Thanks to the textile-integrated electronics, purely textile upholstery and seat covers can obtain additional functions." >>> this was not covered in the thesis, but the sentence is ok because it does not at least claim that the attention was turned to it.
Ref's	62		The list of references is satisfactory, but lacking some interesting references in the period 2004-2010.
List of abbrev.	74-75		- LHCP >> insert "circular" before "polarization" - RHCP >> insert "circular" before "polarization" - UHF >> replace the word "height" with the word "high" - VNA >> insert the word "network" after "vector"
CV	76		- In "Working experience..." - 9/2014 to 12/2020 >>> it is unusual to put the dates from the future in the moment of writing (e.g. 12/2020) - 09/2020 to present >>> 09/2020 is yet to come...
			THANKS!